CA1
DTC 801
85
P51
c.2

arctec canada limited

86-05783/

ARCTEC CANADA LIMITED FR1341C.1

POLAR CLASS ANTARCTIC 1984

LEVEL ICE RESISTANCE TESTS

TP 7183 E

MARCH 1985

BY:

I. Glen,
L. Goossens,
R.P. Voelker,
T. Kotras,
F. Geisel.

Library and Information Centre / Centre de Documentation (GSLA)
RECEIVED - REÇU LE
JUL 4 1986
Transport Canada / Transports Canada

PREPARED FOR:

TRANSPORTATION DEVELOPMENT CENTRE,
Complexe Guy Favreau,
200 Dorchester Blvd. West,
Suite 601, West Tower,
Montreal, Quebec.
H2Z 1X4

PREPARED BY:

ARCTEC CANADA LIMITED,
311 Legget Drive,
Kanata, Ontario.
K2K 1Z8

PROJECT TEAM:

Arctec Canada Limited:	Arctec Engineering Incorporated:
I. Glen	R.P. Voelker
L. Goossens	T. Kotras
	F. Geisel

DISCLAIMER: The contents of this report reflect the views of the contractor and not necessarily those of the Transportation Development Centre.

APPROVED BY:

REPORT DOCUMENTATION FORM

1. Transport Canada Report No.	2. TDC Project No.	3. Recipient's Catalogue No.
7183 E	6031	

4. Title and Subtitle	5. Report Date
POLAR CLASS ANTARCTIC 1984 LEVEL ICE RESISTANCE TESTS	March 1985
	6. Performing Organization Report No FR1341C
7. Author(s)	8. Transport Canada File No.
I. Glen, L. Goossens, R.P. Voelker, F. Geisel	D 1460-181
9. Performing Organization Name and Address Arctec Canada Limited 311 Legget Drive Kanata, Ontario K2K 1Z8	10. DSS File No. 11SD.T8200-3-3517
	11. DSS or Transport Canada Contract No OSD83-00077
12. Sponsoring Agency Name and Address Transportation Development Centre (TDC) 200 Dorchester Blvd. West Suite 601, West Tower Montreal, Quebec H2Z 1X4	13. Type of Report and Period Covered
	14. Sponsoring Agency Code
15. Supplementary Notes See also POLAR CLASS ANTARCTIC 1984 - ICE IMPACT TESTS, I. Glen, C. Daley, J. St. John Arctec Canada Limited, March 1985 - TP 7184 E	16. TDC Project Officer Ian Bayly

17. Abstract

Subsequent to icebreaking resistance tests in thin level ice (under 2 feet, 0.6 m) in the Bering Sea in 1982, a series of tests was performed in thick level ice (3-6 feet, 0.9-1.8 m) at a range of ship speeds and power levels in McMurdo Sound in the Antarctic in January 1985. This data, along with previous resistance data from the Arctic, were used to develop a mathematical relationship describing POLAR class performance in a range of ice thicknesses. Concurrent with the field tests, ice impact loads were measured on an instrumented bow panel. The collected impact data are reported in a companion report, "Polar Class Antarctic 1984 - Ice Impact Tests" (TP 7184E). The results of the resistance tests were used to evaluate two semi-empirical ice resistance prediction models. The most recently developed and more advanced model gave good predictions for ice resistance, after the model was updated using the latest resistance data.

18. Key Words	19. Distribution Statement
Antarctica, Design Criteria, Ice Impact Loads, Ice Pressure, Measurement, Shipboard Loads.	Limited number of copies available from the Transportation Development Centre.

20. Security Classification (of this report)	21. Security Classification (of this page)	22. No. of Pages	23. Price
unclassified	unclassified	118	nil

TDC CDT 79-005

FORMULE DE DOCUMENTATION POUR RAPPORT

1. N° du rapport Transports Canada	2. N° de l'étude — CDT	3. N° de catalogue du destinataire
7183 E	6031	

4. Titre et sous-titre	5. Date du rapport
POLAR CLASS ANTARCTIC 1984 LEVEL ICE RESISTANCE TESTS	mars 1985
	6. N° du rapport de l'organisme exécutant FR1341C
7. Auteur(s) I. Glen, L. Goossens, R.P. Voelker, F. Geisel	8. N° de dossier Transports Canada D 1460-181
9. Nom et adresse de l'organisme exécutant Arctec Canada Limited 311 Legget Drive Kanata, Ontario K2K 1Z8	10. N° de dossier — ASC 11SD.T8200-3-3517
	11. N° de contrat — ASC ou Transports Canada OSD83-00077
12. Nom et adresse de l'organisme parrain Centre de développement des transports (CDT) 200 ouest, boul. Dorchester Suite 601, tour ouest Montréal, Québec H2Z 1X4	13. Genre de rapport et période visée
	14. Code de l'organisme parrain
15. Remarques additionnelles Voir également "POLAR CLASS ANTARCTIC 1984 - ICE IMPACT TESTS", I. Glen, C. Daley, J. St.John Arctec Canada Limited, mars 1985 - TP 7184 E	16. Agent de projet — CDT Ian Bayly

17. Résumé

Ce rapport concerne les essais de résistance à l'avancement dans des glaces uniformes de forte épaisseur (de 3 à 6 pieds ou 0,9 à 1,8 m), effectués dans le détroit McMurdo dans l'Antarctique en janvier 1985, à vitesse et puissance variables; ces essais étaient la continuation de ceux qui ont eu lieu en 1982 dans la mer de Béring, dans des glaces uniformes de faible épaisseur (moins de 2 pieds, 0,6 m). Les données recueillies, s'ajoutant à celles obtenues dans l'Arctique, ont servi à élaborer un modèle mathématique représentant les performances des navires de classe POLAR dans des épaisseurs de glace variables. Simultanément, la charge des glaces a pu être mesurée grâce à un panneau instrumenté à l'avant du navire. Les données enregistrées sur les impacts sont consignées dans le rapport TP 7184 E intitulé "Polar Class Antarctic 1984 - Ice Impact Tests" qui accompagne le présent rapport. Grâce à ces essais sur la résistance des glaces, il a été possible d'évaluer deux modèles semi-empiriques figurant cette résistance, et dont le deuxième, le plus récent et le plus avancé des deux, a fourni des bonnes prévisions de résistance après qu'il eut été affiné par la prise en compte des données les plus récentes.

18. Mots-clés	19. Diffusion
Antarctique, critères de calcul, charge des glaces, pression des glaces, mesure des charges.	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

20. Classification de sécurité (de ce rapport)	21. Classification de sécurité (de cette page)	22. Nombre de pages	23. Prix
non classifié	non classifiée	118	-

SUMMARY AND CONCLUSIONS

Icebreaking resistance data and ice pressures on an instrumented bow panel were collected in McMurdo Sound, Antarctica onboard the USCGC POLAR SEA during January 9-13, 1984. The results of icebreaking resistance tests are given in this report and the results from the ice pressure data collection effort are presented in "Polar Class Antarctic 1984 - Ice Impact Tests [6]. The summary and conclusions for the icebreaking resistance test portion of this project, (with reference to the report section from which they came) are:

- Ice conditions in McMurdo Sound were excellent for level ice resistance testing. Thickness variations of only a few centimetres were normally recorded in .8 km distances. The majority of tests were performed in ice thicknesses between 4 and 6 feet (1.23 to 1.83 m). The depth of snow (averaging about 1 to 2 inches (3 to 5 cm) was inconsequential in terms of contributing to icebreaking resistance, (2.1, 2.2).

- The mean flexural strength during the five day test period was 44 psi (303.4 kPa). This compares favourably with flexural ice strength measurements in the Arctic Bering Sea, (2.3).

- Thirty icebreaking resistance data points were obtained in Antarctic level ice of 3 to 6 feet (.9 m to 1.8 m) at speeds as high as 12 knots. This data, together with 34 data points collected in the Arctic in 1982 in ice thicknesses ranging from 0.6 to 1.6 feet (.18 m to .49 m) and at speeds up to 14.3 knots, provides a good basis upon which to derive full scale icebreaking performance estimates, (3.1, 3.2).

- The equation that best describes the performance of the POLAR Class is:

$$R_i = 3.6\ \rho g\ Bh^2 + 0.2\ \rho g^{1/2}\ B^{1/2}\ LVh$$

where: R_i = ice resistance in N
ρ = mass density of sea water (kg/m^2)
g = gravitational acceleration in m/sec^2
B = ship maximum beam at waterline in m
h = ice thickness in feet (m)
L = length between perpendiculars in m
V = ship speed in feet/second (m/sec)
(3.3,3.4,3.5)

- Based on a regression analysis of available full scale data, the POLAR Class icebreaking capability at 60,000 shaft horsepower is approximately 6 feet (1.8 m) at 3 knots, (3.5).

- Icebreaking dynamics in thick ice of 5 to 6 feet (1.5 to 1.8 m) at slow speeds (0 to 3 knots) is significantly different than in thin ice of 1 to 2 feet (.3 to .6 m) at corresponding

slow speeds. In thick ice, the icebreaker pitches and rolls as a result of breaking large ice pieces at the bow. Some of these pieces (defined as cusps) were 100 feet (30.5 m) in length by 30 feet (9.1 m) in width measured alongside the ship. Subsequently, these cusps would fail in two or more pieces as the ship moved forward. Noteworthy is the fact that project personnel were readily able to cross the newly broken ice channel by moving from one large ice floe to the next. Some of the ice floes were as large as 40 feet (12.2 m) in length, but many were about 20 feet (6.1 m) in diameter.

- A number of ice thickness measurements were made with a new remote thickness meter (AIM). This meter permits a direct readout of thickness without the augering of holes. A comparison of augered thicknesses to AIM readings showed excellent agreement with less than a 10% difference between the two methods, (Appendix D).

- Approximately 1,000 ice impact events were recorded on the instrumented bow panel in ice thicknesses ranging from 3 to 6 feet (.9 to 1.8 m) and at speeds up to 12 knots. These data were collected concurrently with the level ice resistance tests and during the broken ice channel preparations for the Antarctic resupply ships. Excellent video data was also obtained from the bow camera showing ice impacts at the instrumented panel and cusp breaking. This aspect of the test program has been reported in "Polar Class Antarctic 1984 - Ice Impact Tests [6].

- Two semi-empirical ice resistance prediction models have been evaluated. The first model RICE did not give satisfactory resistance predictions for the USCGC POLAR SEA. The model requires to be updated since the development started several years ago. However, new developments were implemented in a second, more advanced model SPLICE, which was updated using the results of the recent resistance data. This model gave good predictions of the resistance and is recommended for future work on level ice resistance, (3.6, Appendix E, F).

SOMMAIRE ET CONCLUSIONS

Ce rapport concerne les travaux de mesurage de la résistance des glaces et de la pression exercée par celles-ci sur un panneau instrumenté placé à l'avant du brise-glace américain POLAR SEA; ces travaux ont eu lieu du 9 au 13 janvier 1984 dans le détroit McMurdo, dans l'Antarctique. Il présente les résultats du mesurage de la résistance des glaces, tandis que ceux relatifs au mesurage des pressions sont consignés dans le rapport intitulé "Polar Class Antarctic 1984 - Ice Impact Test (6)". Le résumé et les conclusions des travaux concernant le mesurage de la résistance des glaces (tirés des sections indiquées) sont les suivants:

- Les conditions glacielles dans le détroit McMurdo ont été trouvées excellentes pour les essais de résistance dans des glaces uniformes, des variations de quelques centimètres seulement ayant été constatées sur des distances de 0,8 k.m. La plus grande partie des essais a eu lieu dans des glaces d'une épaisseur comprise entre 4 et 6 pieds (1,23 à 1,83 m). L'épaisseur de la couche de neige, en moyenne de 1 à 2 pouces (3 à 5 cm), n'a eu aucune influence sur la résistance à l'avancement proprement dite (2.1, 2.2).

- La résistance moyenne à la rupture en flexion mesurée au cours des cinq jours qu'ont duré les essais a été de 44 lb/po^2 soit 303,4 kPa. Elle se compare avantageusement à celle des glaces dans la mer de Béring (2.3).

- Les essais dans l'Antarctique dans une glace uniforme d'épaisseur variant entre 3 et 6 pieds (0,9 à 1,8 m), et à une vitesse de marche maximale de 12 noeuds, ont livré des données sur 30 paramètres différents, comparativement aux 34 paramètres mesurés lors des essais dans l'Arctique en 1982 dans une glace d'une épaisseur variant entre 0,6 et 1,6 pied (0,18 à 0,49 m) et à la vitesse maximale de 14,3 noeuds. Ensemble, ces données constituent une assise solide sur laquelle fonder des prévisions concernant la résistance à l'avancement in situ.

- La formule suivante rend bien compte de cette résistance, dans le cas du POLAR SEA:

$$R_i = 3.6\ pg\ Bh^2 + 0.2\ pg^{1/2}\ B^{1/2}\ LVh$$

où: R_i = résistance de la glace en N
p = masse volumique de l'eau de mer (kg/m^3)
g = accélération due à la pesanteur en m/s^2
B = maître bau du navire à la ligne de flottaison en m
h = épaisseur de la glace en pieds (m)
L = longueur entre perpendiculaires en m
V = vitesse de marche en pieds/s (m/s)
(3.3, 3.4, 3.5)

- L'analyse par la méthode de régression à partir des essais in situ a démontré que le POLAR SEA peut briser des glaces de l'ordre de 6 pieds (1,8 m) d'épaisseur lorsqu'il avance à 3 noeuds et développe 60 000 Hp à l'arbre.

- La marche dans une glace de 5 à 6 pieds (1,5 à 1,8 m) d'épaisseur à faible vitesse (0 à 3 noeuds) fait naître des forces dynamiques sensiblement différentes de celles qui s'exercent aux mêmes faibles vitesses lorsque l'épaisseur de la glace est plus mince (1 à 2 pieds ou 0,3 à 0,6 m). Dans le premier cas, le brise-glace tangue et roule sous l'action des gros morceaux de glace qui se brisent à mesure qu'il avance. Certains morceaux, mesurés au droit de la coque, avaient 100 pieds (30,5 m) de long sur 30 pieds (9,1 m) de large. Par la suite, ces morceaux se brisent en deux morceaux plus petits ou plus à mesure que le navire avance. Il est intéressant de faire observer qu'il a été possible aux chercheurs de passer d'un côté à l'autre du chenal ouvert par le navire en sautant d'un floe à l'autre, certains pouvant avoir jusqu'à 40 pieds (12,2 m) de long, mais la plupart n'ayant que 20 pieds (6,1 m) au maximum.

- Des essais de mesurage de l'épaisseur de la glace ont été faits à l'aide d'un nouvel appareil de télémesure (AIM), qui remplacerait le sondage mécanique de la glace à la tarière. Le résultat des télémesures comparées aux mesures effectuées mécaniquement a montré une très bonne corrélation, l'écart étant de moins de 10 p. 100. (Annexe D).

- Près d'un millier d'impacts ont été enregistrés au droit du panneau instrumenté, le navire avançant à 12 noeuds ou moins dans une glace ayant de 3 à 6 pieds (0,9 à 1,8 m) d'épaisseur. Ces enregistrements ont eu lieu en même temps que s'effectuaient les essais de résistance à la marche et que le navire ouvrait un chenal pour le passage des navires d'approvisionnement. Des données magnétoscopiques d'excellente qualité ont aussi été obtenues grâce à la caméra placée à l'avant du navire et montrant l'action de déglaçage et le fractionnement de la glace. Cet aspect de la recherche a fait l'objet du compte rendu intitulé "Polar Class Antarctic 1984 - Ice Impact Tests (6)".

- Deux modèles semi-empiriques figurant la résistance des glaces ont été évalués. Le premier appelé RICE n'a pas donné les résultats escomptés, les valeurs de résistance calculées à l'égard du POLAR SEA n'ayant pas été jugées satisfaisantes. Ce modèle doit être affiné, d'autant plus qu'il commence à dater. Mais un deuxième modèle plus avancé, appelé SPLICE, a fourni de bonnes prévisions de résistance après qu'il eut été affiné par la prise en compte des données récemment colligées. C'est ce modèle qui a été recommandé pour les travaux futurs de prévisions de résistance concernant les glaces uniformes (3,6, annexes E et F).

TABLE OF CONTENTS

SUMMARY AND CONCLUSIONS

1. DESCRIPTION OF THE TEST PROGRAM....2

2. ICE CHARACTERISTICS....4
   2.1 General Appearance....4
   2.2 Ice Thickness....6
   2.3 Ice Strength....8

3. LEVEL ICE RESISTANCE....10
   3.1 Data Matrix....10
   3.2 Results from January 1984 Tests....12
   3.3 Resistance Prediction Based on 1984 Data....14
   3.4 Resistance Prediction Based on 1982 Data....16
   3.5 Resistance Prediction Based on Combined 1984 and 1982 Data....18
   3.6 Comparison with Ice Resistance Prediction Models....20

4. OBSERVATIONS AND NOTES REGARDING THE 1984 DATA COLLECTION....22

5. RECOMMENDATIONS....24

6. REFERENCES....26

APPENDICES A - ICE CORE DATA AND ESTIMATES OF FLEXURAL STRENGTH

B - 1984 POLAR SEA RESISTANCE DATA

C - METEOROLOGICAL CONDITIONS DURING TEST PERIOD FROM PILOT HOUSE LOGS

D - COMPARISON OF ARCTEC ICE-THICKNESS METER READINGS TO DATA FROM AUGERING

E - COMPARATIVE ANALYSIS OF ANTARCTIC LEVEL ICE RESISTANCE DATA OF THE USCGC POLAR SEA (RICE MODEL)

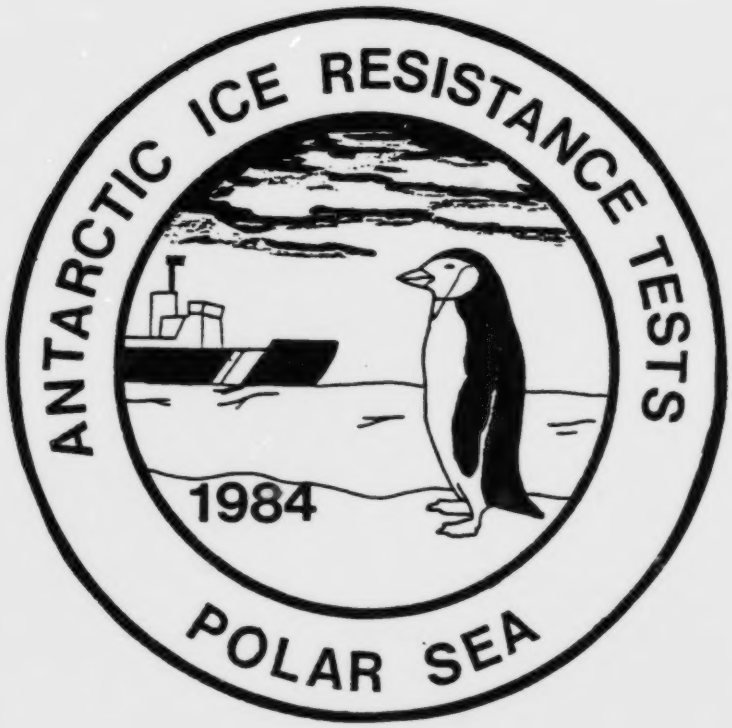
F - UPDATE SEMI-EMPIRICAL ICE RESISTANCE PREDICTION EQUATIONS (SPLICE MODEL)

LIST OF FIGURES

1.1 PRINCIPAL FEATURES OF A POLAR CLASS ICEBREAKER.....3
2.1 TEST SITE IN MCMURDO SOUND.....5
2.2 PRE-TEST SURVEY OF ICE CONDITIONS IN FRONT OF POLAR SEA.....6
2.3 ICE THICKNESS DISTRIBUTION IN ANTARCTIC TEST AREA.....7
3.1 POLAR CLASS LEVEL ICE TEST DATA.....11
3.2 THRUST AND SHIP SPEED VARIATION.....13
3.3 RESISTANCE PREDICTION BASED ON 1984 DATA.....15
3.4 RESISTANCE PREDICTION BASED ON 1982 DATA.....17
3.5 RESISTANCE PREDICTION BASED ON 1982 & 1984 DATA COMBINED.....19
3.6 POLAR CLASS.....21

LIST OF TABLES

2.1 SEA ICE STRENGTH.....9
3.1 ICE RESISTANCE DATA.....12
3.2 LEVEL ICE RESISTANCE DATA POINTS.....16
3.3 SUMMARY OF REGRESSION COEFFICIENTS.....18


ANTARCTIC ICE RESISTANCE TESTS
1984
POLAR SEA

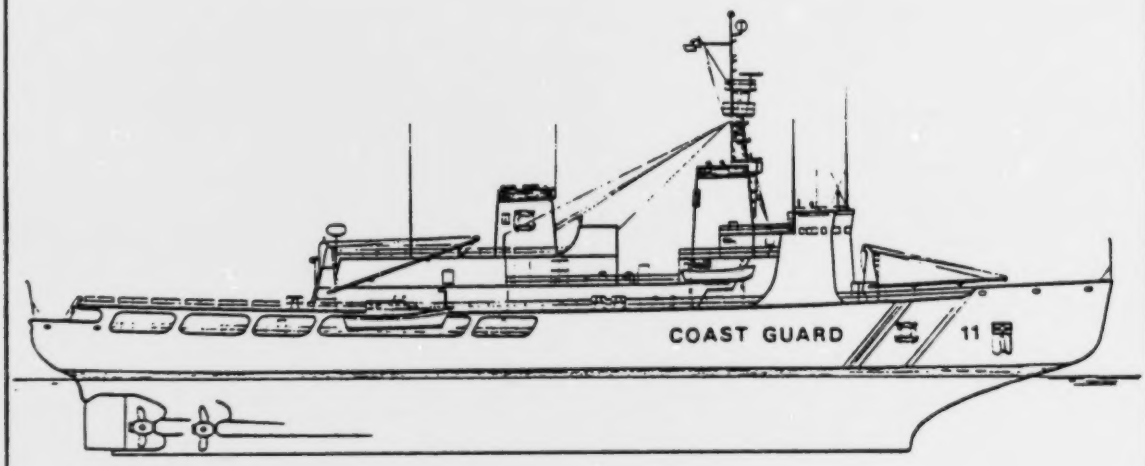
1. DESCRIPTION OF THE TEST PROGRAM

The USCGC POLAR SEA's January 1984 Test Program was developed in order to take advantage of the thick level ice conditions available in the Antarctica to augment the data base of Polar Class (Figure 1.1) performance in ice thicknesses up to 6 feet (1.83 m). Although the focus of the program was always directed at level ice resistance, it appeared, from a planning point of view, that a number of additional tests or data collection efforts could be performed if time became available. Priorities for the data collection effort were established at a pre-test planning meeting and documented in the preliminary test plan [1] as follows:

Priority	Test Description
1	Level Ice Resistance
2	Ice Loads on Instrumented Bow Panel Measurement of Ice Cusp Size and Channel Width
3	Ramming Resistance in Level Ice with Diesels Ice Impact During Scarfing Broken Ice Resistance Level Ice Resistance with Heeling System in Operation Parallel Track Level Ice Resistance

The primary objectives were identified as Level Ice Resistance and Loads data collection. Because of a number of operational factors, the time available for the testing was five days. Daily shipboard test requirements were kept at less than eight hours so that the remaining hours could be used for other operational needs, such as channel preparation for the Antarctic resupply ships. Within the five day availability period, instrumentation was connected, tests were performed, and equipment disassembled and stored. With such time constraints the major effort was devoted to the level ice resistance data collection and first-pass data analysis. The instrumentation system and data collection for the measurement of ice loads (Priority 2) were totally independent of the system required for ice resistance. Instrumentation for this system was also installed, data collected, and the equipment disassembled within the five day time period. The results of these measurements are reported in "Polar Class Antarctic 1984 - Ice Impact Tests", TP7184E, [6].

Other Priority 2 activities, - measurement of ice cusp size and measurement of channel width, were not achieved by the on-ice profiling team due to the time required for ice thickness profiling and the taking of ice cores. Ice cusp size may be determined from the video tapes of the over-the-side camera and the still photos taken, as both were calibrated. Such post test analysis was beyond the scope of the present project however. Similarly, none of the Priority 3 objectives were met due to the fact that the entire project team was working on level ice resistance data collection and analysis. In many cases, ramming operations with diesels were performed, as well as parallel track ice-breaking, and operations in a broken ice channel. Resistance data collection during these operations was, however, infeasible because of



SHIP STATISTICS:

LENGTH OVERALL	399 FEET (121.6 m)
LENGTH AT WATERLINE	352 FEET (107.3 m)
BEAM	83.5 FEET (25.3 m)
DRAFT	31.8 FEET (9.7 m)
DISPLACEMENT, CAPACITY LOAD	13,190 TONS
RANGE (MAXIMUM)	28,274 MILES
SUSTAINED SPEED (OPEN WATER)	17 KNOTS
PROPULSION	DIESEL ELECTRIC OR GAS TURBINE
SHP	18,000 D-E 60,000 G-T
NUMBER OF SCREWS	3
COMPLEMENT	14 OFFICERS 126 ENLISTED
SCIENTIST ACCOMMODATIONS	20
HEIGHT OF BRIDGE ABOVE WATERLINE	55 FEET (16.8 m)
HEIGHT OF ALOFT CONN ABOVE WATERLINE	104 FEET (31.7 m)

FIGURE 1.1

PRINCIPAL FEATURES OF A POLAR CLASS ICEBREAKER

onboard data analysis of level ice resistance and collection of impact loads. An additional two to three days would have been needed to achieve all of the Priority 2 and 3 objectives.

In summary, due to restrictions on onboard manpower, and lack of dedicated testing time, only the primary objectives of the data collection effort were met. All collected data have been included in Appendices A, B, C, and D.

2. ICE CHARACTERISTICS

2.1 General Appearance

This section presents the results of visual observations of the ice in McMurdo Sound during:

1. Initial helicopter flight to board the ship from McMurdo Sound to the ice edge on 9 January 1984.

2. Helicopter ice reconnaissance flight over the outer half of the landfast ice on 11 January 1984.

3. Daily icebreaking to prepare a channel for the resupply ships from the ice edge to Hut Point.

4. Daily on-ice augering along the broken ice channel.

The test site of the experimental program is shown in Figure 2.1.

Ice in McMurdo Sound was undisturbed compared to typical Arctic conditions; i.e., rafting and rubble ice piles were not evident. Linear thermal or wind stress cracks ran east-west across McMurdo Sound at spacings measured in hundreds of metres. No such features were observed in the north-south direction. Most of these cracks had opened a few metres and refrozen. In a few cases, these refrozen cracks were subsequently compressed and very small (1.5 feet (.5 m) high) pressure ridges formed. One of these cracks, about halfway between Hut Point and the ice edge, separated what appeared to be two very different ice regimes. South of the crack (close to Hut Point) the ice was more rotten with many melt ponds, and north of the crack (toward the ice edge) it was very smooth with very few melt ponds. The area north of the crack, which included the test area, was whiter and less moist in appearance than that south of the crack. One possible explanation is the prevailing wind (from the southeast) had warmed over the bare ground portions of Ross Island causing the ice to deteriorate more rapidly nearshore than at the outer half of landfast ice. The meteorological conditions during the test period are given in Appendix C. Snow cover on the ice was very thin; averaging about two inches (5 cm). Some areas had accumulated drifts of a few centimetres and others were swept clean. Generally, the snow cover was firm, indicating possible freeze-thaw cycles. There was very little dry powder snow.

During ship resistance testing and the more general icebreaking required to prepare a channel for the resupply tanker, large ice pieces were flipped 180 degrees such that the bottom ice surface could be

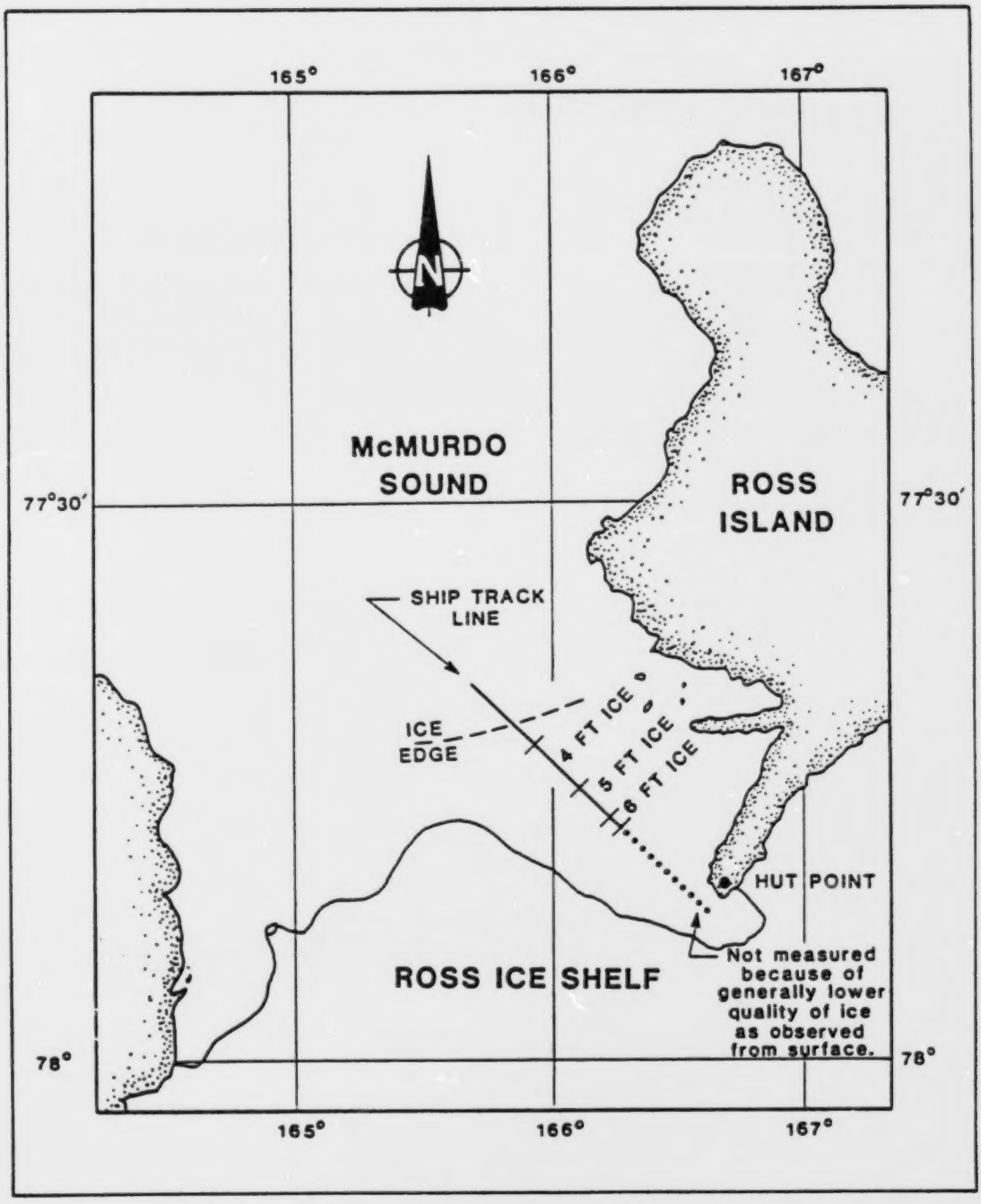


FIGURE 2.1

TEST SITE IN MCMURDO SOUND

examined. In all cases, the bottom ice surface was very smooth; in some cases very flat, in other cases irregular with an observed surface variation of less than about three to four inches (8 to 10 cm).

In summary, the ice in McMurdo Sound proved excellent for level ice resistance testing. Thickness variations are generally small (a few centimetres) within .8 km distances. The depth of snow on the ice surface was inconsequential in terms of contributing to icebreaking resistance. The following section describes the ice thickness measurements in more detail.

2.2 Ice Thickness

Level icebreaking resistance testing in the Antarctic proved most successful because of the large areal extent of uniformly thick ice. Prior resistance testing in the Arctic had been performed in level ice floes of under two feet (.6 m) in thickness: thicker floes difficult and time consuming to locate.

After boarding POLAR SEA on January 9, a pre-test ice survey was initiated. The results from auger tests are shown in Figure 2.2 and were used as a guide to plan the detailed test program.

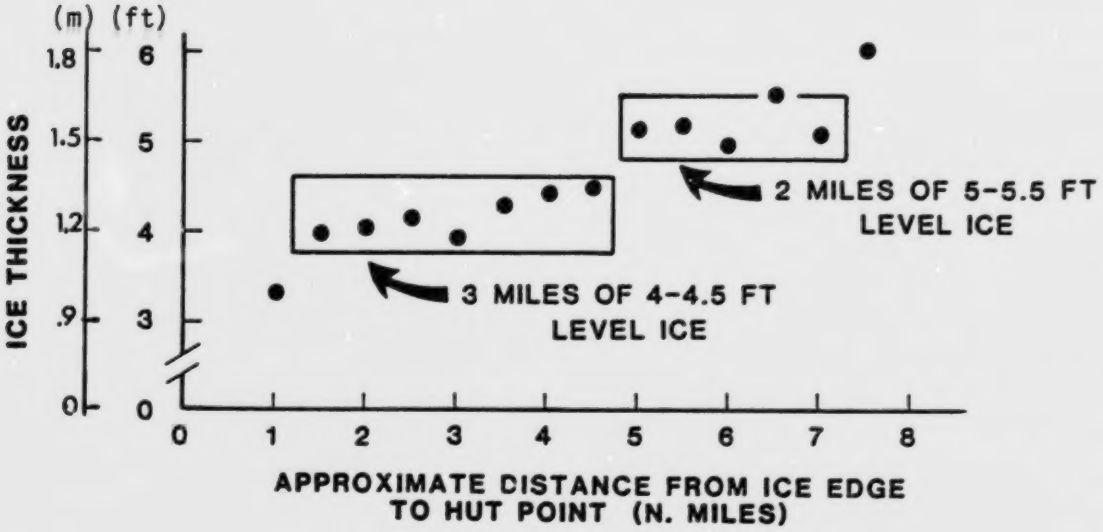


FIGURE 2.2
PRE-TEST SURVEY OF ICE CONDITIONS IN FRONT OF POLAR SEA

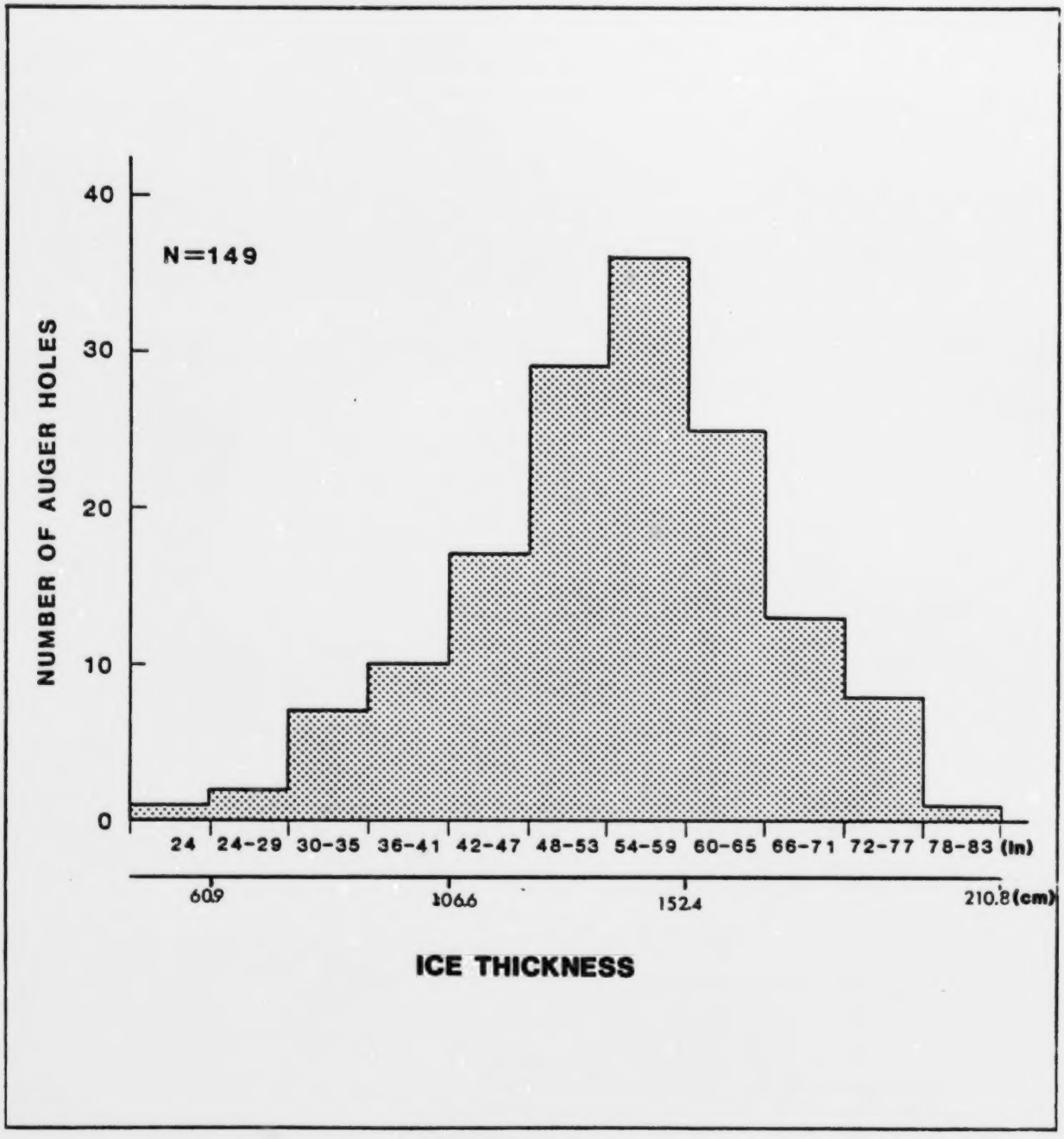


FIGURE 2.3

ICE THICKNESS DISTRIBUTION IN ANTARCTIC TEST AREA

As a result, it was decided to conduct the steady-state resistance tests first and to determine the ice thickness subsequently.

The prime technique for measuring ice thickness was augering a four inch (10.1 cm) diameter hole and then measuring the ice thickness with a calibrated rod. In addition, an electronic ice thickness measuring instrument was used to determine thickness between holes (see Appendix D). A total of 149 direct measurements were made and their distribution is shown in Figure 2.3. Although ice thickness ranged from 16 to 78 inches (40.6 - 198 cm), the majority was between 48 and 60 inches (121.9 - 152.4 cm). The 16 inch (40.6 cm) measurement was in a refrozen lead and the other, thinner measurements were taken closer to the ice edge. The primary test area proved to be the track line used by POLAR SEA to escort the resupply tanker and in one case, a parallel track was used.

2.3 Ice Strength

Sea ice strength was based on measured values of ice temperature and salinity from ice cores. Based on the values recorded, a flexural ice strength is inferred from prior experiments equating salinity and temperature to cantilever beam tests of the ice. Appendix A gives the mathematical relationship.

Ice temperature profiles were measured at 4 inch (10.1 cm) intervals in each of the six cores taken during the test period. All ice temperatures were unexpectedly warm. The coldest temperature was -3.7°C. These warm temperatures were the result possibly of a rotten, very porous ice layer about 12 inches (30.5 cm) from the surface allowing salt water immersion of the cores. All six core holes became flooded at a depth of about 12 inches (30.5 cm). Only one core had a temperature profile consistently above the freezing temperature of sea ice (-1.8°C).

Ice salinities were obtained by measuring the conductivity of melt water from ice samples collected at 6 inch (15.2 cm) intervals in the cores. Salinities were comparable to Arctic first year sea ice at breakup. Salinities near the surface were 1-3 PPT, and near the bottom were 4-6 PPT. These salinities do not indicate salt water saturation of the cores as a result of immersion of the ice core. The salinities are indicative of normal strength first year sea ice; however, the temperatures are indicative of weak sea ice.

Examination of full depth failure surfaces caused by the ship were quite normal in appearance, except for the porous layer discussed previously. The bottom surface of the ice was very smooth with no skeletal layer commonly seen on the bottom of arctic sea ice. This lack of a skeletal layer could be the result of the deterioration of the ice or mechanical disturbance in the icebreaking process. Another indirect observation was made during the augering of thickness holes. The resistance to augering was comparable to that in Arctic sea ice. In the upper 12 inches (30.5 cm) (above the porous layer) the ice chips were dry, shiny, and very similar in appearance to multiyear ice chips. Below the porous layer the chips were wet and the resistance to augering increased, probably because of the increased weight of the chips. This

latter observation is consistent with Arctic experience in warm first year ice. Although the gross structure of the ice appeared normal, only detailed cyrstallographic analysis can yield a good comparison with Arctic sea ice.

Table 2.1 summarizes the results from the temperature-salinity measurements from ice cores. To determine a representative ice strength during the five day test program, it was decided to calculate the mean value using the upper 75% of the ice core and the total length of the ice core. The first core was not used in the analysis as Core Number 2 was taken a few metres from the first core and gave a more characteristic value. Core Number 6 was not used because the ice temperatures recorded were above the freezing point of ice. All equipment was calibrated before and after the measurments and the readings from Core No. 6 are therefore suspect. Although it would have been desirable to obtain a greater number of ice cores, circumstances precluded that. One sample of sea water was taken and the salinity measured at 32.5 PPT at a temperature of 0.6°C.

A mean value of 43.90 psi (302.7 kPa) and 44.50 psi (306.9 kPa) were determined for the case of using 75% of the upper ice core and the total core, respectively. From this, it was concluded that 44 psi (303.4 kPa) is a fair representation of the flexural ice strength during the test program.

TABLE 2.1

SEA ICE STRENGTH

CORE NO.	ICE THICKNESS		SEA ICE STRENGTH FOR UPPER 75% OF CORE		SEA ICE STRENGTH FOR TOTAL THICKNESS OF CORE	
	(inches)	(cm)	(psi)	(kPa)	(psi)	(kPa)
1	42	106.7	26.4	182.0	25.6	176.5
2	38	96.5	48.3	333.0	52.4	361.3
3	72	182.8	37.4	257.9	35.8	246.8
4	68	172.7	45.8	315.8	46.2	318.5
5	68	172.7	44.2	304.8	43.9	302.7
6	70	177.8	33.5	231.0	37.2	256.5

3. LEVEL ICE RESISTANCE

3.1 Data Matrix

To accurately determine the icebreaking capabilities of the POLAR Class, full scale resistance data is needed in a wide range of ice thicknesses and speeds. During a previous resistance data collection program aboard the POLAR STAR in the Bering Sea in April 4-14, 1982, 34 data points were obtained in ice thicknesses ranging from 0.6 to 1.6 feet (.2 to .5 m) and at ship speeds from 0.6 to 14.3 knots. 1982 was an unusually light ice year and greater ice thicknesses were not present. As this 1982 data set represented only about 25% of the designed icebreaking capability of the POLAR Class, it was deemed important to obtain data in the thicker ice of the Antarctic. In these tests, reported herein, 30 data points were collected in ice thicknesses ranging from 3 to 6 feet (.9 to 1.8 m) at speeds from 1 to 12 knots.

A matrix of the 1982 and 1984 ice resistance data is shown in Figure 3.1. Within each box, the number of data points is stated for that ice thickness and speed. It should be noted that a box showing a ship speed of between 2 to 3 knots is actually for speeds of 2.0 knots to 2.99 knots and the 3.0 knot speed is in the box labelled 3 to 4 knots. The matrix shows that a good set of data exists from which the POLAR Class icebreaking capability can be defined. The matrix also identifies desirable conditions for future test programs on this vessel.

During level ice testing the following parameters were recorded continuously for each propeller shaft: thrust, torque, propeller pitch, shaft rpm, and ship speed.

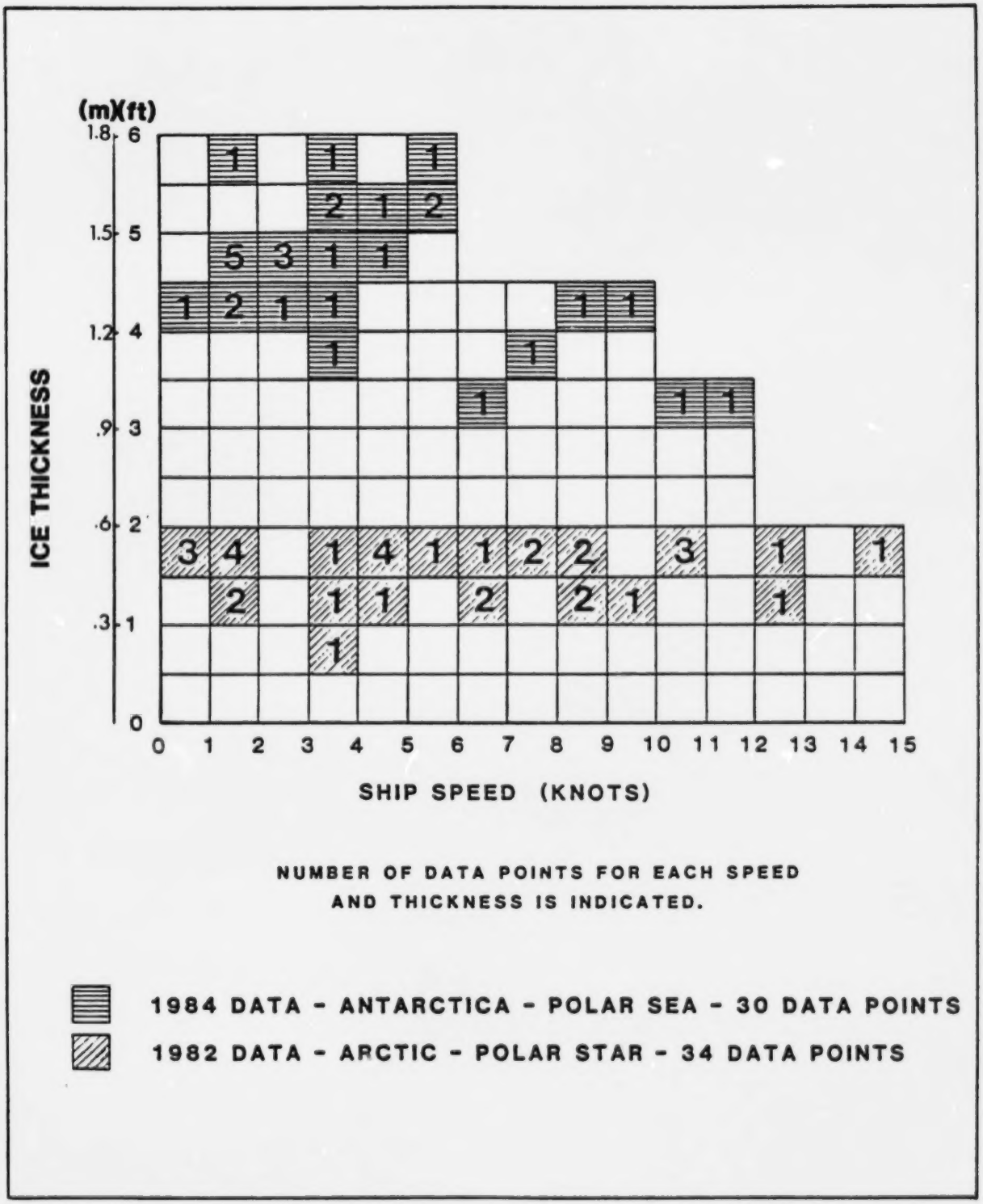

(mX ft)
1.8 6
1.5 5
1.2 4
.9 3
.6 2
.3 1
0
ICE THICKNESS
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
SHIP SPEED (KNOTS)
NUMBER OF DATA POINTS FOR EACH SPEED
AND THICKNESS IS INDICATED.
1984 DATA - ANTARCTICA - POLAR SEA - 30 DATA POINTS
1982 DATA - ARCTIC - POLAR STAR - 34 DATA POINTS

FIGURE 3.1

POLAR CLASS LEVEL ICE TEST DATA

3.2 Results From 1984 Tests

Level ice resistance tests were performed during January 9-13, 1984 in McMurdo Sound, Antarctica. A total of 30 data points were obtained in ice thicknesses ranging from 3 to 6 feet (.9 to 1.8 m) and at speeds up to 12 knots. A tabular listing of the data is given in Table 3.1 and an example of the thrust and ship speed variation during the steady-state run of data point number 004.1 is shown in Figure 3.2. It should be noted that the 270 second interval at 5.9 knots represents approximately a .8 km distance for the test run. Appendix B shows a similar graphical display of propeller thrust and ship speed for all of the data points. For reasons discussed in Section 4, data at low speeds (<2 knots) and test series 9-13 are considered the least accurate, but overall accuracy of the data is estimated to be within ±10%.

TABLE 3.1
ICE RESISTANCE DATA

TEST NO.	DATE	ICE THICKNESS (ft)	(m)	AVERAGE SPEED (kts)	ICE RESISTANCE (lbs)	SHAFT HORSEPOWER	PROPULSION PLANT CONFIGURATION
001.1	1/9/84	4.00	1.22	1.1	350,620	11,308	DD/GT/DD
001.2	1/9/84	4.00	1.22	3.5	446,112	19,229	DD/GT/DD
001.3	1/9/84	4.25	1.30	0.9	231,846	14,190	DD/GT/DD
002.1	1/10/84	4.25	1.30	1.3	321,865	13,675	DD/DD/DD
002.2	1/10/84	4.58	1.40	2.0	396,692	17,379	DD/DD/DD
002.3	1/10/84	4.58	1.40	2.2	398,611	16,263	DD/DD/DD
003.1	1/10/84	4.67	1.42	1.4	363,319	23,597	GT/GT/GT
003.2	1/10/84	4.75	1.45	3.3	435,360	30,113	GT/GT/GT
003.3	1/10/84	5.08	1.55	4.9	590,943	38,717	GT/GT/GT
004.1	1/10/84	5.33	1.62	5.9	747,206	51,225	GT/GT/GT
005.2	1/11/84	4.83	1.47	1.5	373,889	25,793	GT/GT/GT
005.3	1/11/84	5.42	1.65	3.0	476,723	35,251	GT/GT/GT
005.4	1/11/84	5.17	1.58	3.2	531,968	35,460	GT/GT/GT
006.1	1/11/84	5.71	1.74	3.7	605,490	38,915	GT/GT/GT
007.1	1/11/84	5.92	1.80	5.7	825,289	57,400	GT/GT/GT
008.1	1/12/84	4.42	1.35	8.2	659,230	51,342	GT/GT/GT
008.2	1/12/84	4.92	1.50	2.8	514,655	31,513	GT/GT/GT
008.3	1/12/84	4.58	1.40	4.5	503,711	35,604	GT/GT/GT
008.4	1/12/84	4.17	1.27	9.2	591,073	49,804	GT/GT/GT
008.5	1/12/84	3.08	.94	10.9	476,022	42,516	GT/GT/GT
008.6	1/12/84	3.33	1.01	11.2	489,067	42,615	GT/GT/GT
009.1	1/13/84	5.50	1.68	1.0	613,790	18,251	GT/DD/GT
010.1	1/13/84	4.83	1.47	1.2	263,832	19,517	GT/DD/GT
011.1	1/13/84	5.17	1.58	5.5	574,006	38,669	GT/DD/GT
011.2	1/13/84	4.50	1.37	1.1	442,581	19,129	GT/DD/GT
011.3	1/13/84	4.92	1.50	1.8	560,017	22,290	GT/DD/GT
012.1	1/13/84	4.42	1.35	2.6	331,640	24,617	GT/DD/GT
013.1	1/13/84	3.83	1.17	7.0	499,645	34,729	GT/DD/GT
013.2	1/13/84	3.92	1.19	3.3	382,414	21,700	GT/DD/GT
013.3	1/13/84	3.08	.94	6.0	375,989	29,801	GT/DD/GT

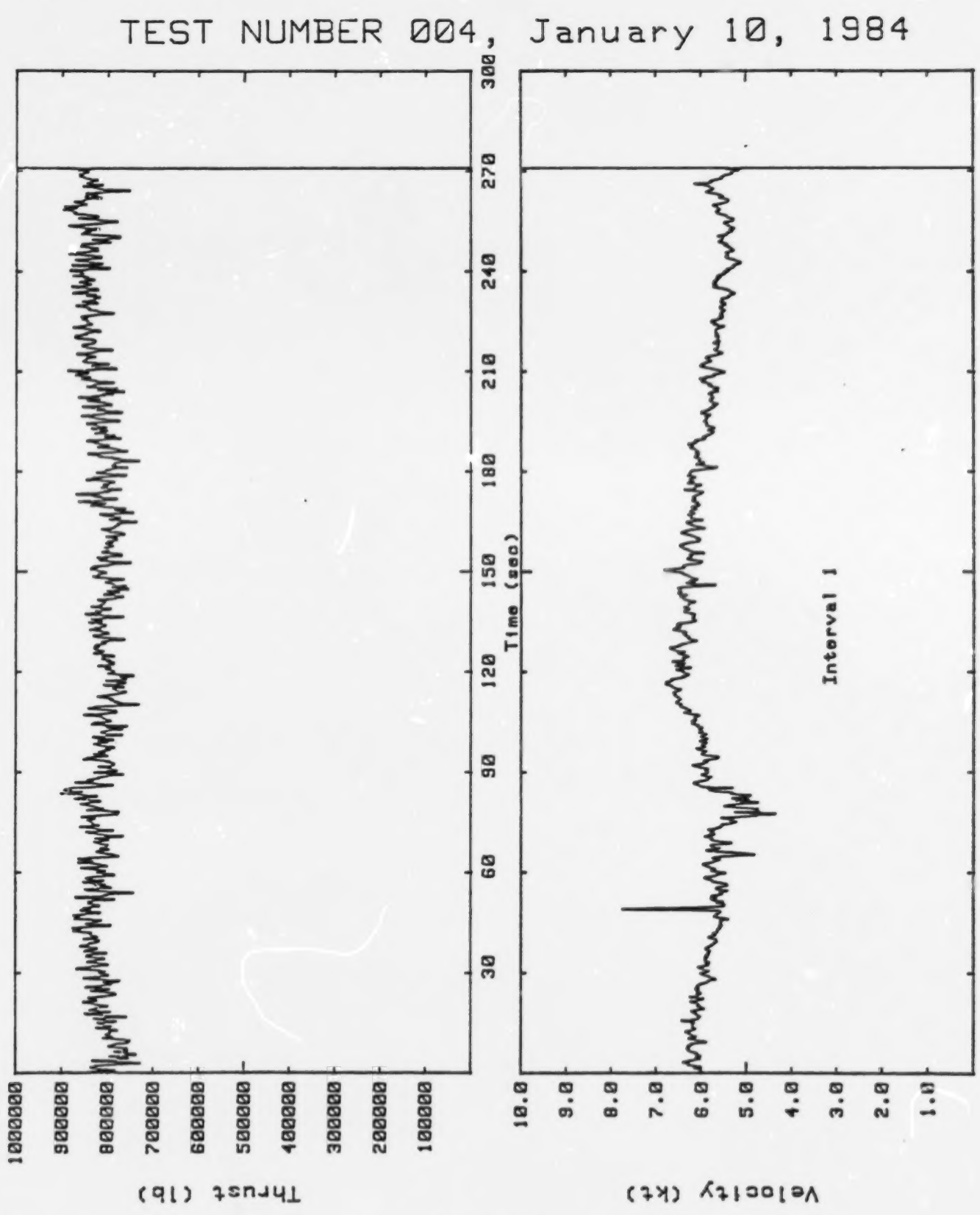


FIGURE 3.2
THRUST AND SHIP SPEED VARIATION

3.3 Resistance Prediction Based on 1984 Data

Analysis of test data determined the steady-state time periods, and averages of each measured parameter were calculated for those periods. Over the same steady-state periods, average propeller pitch, shaft rpm, and ship speed were used to calculate t, thrust deduction, based on an empirical relationship developed after full scale bollard and tow-rope tests conducted on POLAR SEA in 1980. One of the primary results from that testing (see Reference [2], Volume V) showed that the thrust deduction factor can be expressed as a function of propeller loading by the pitch-to-diameter (P/D) ratio and advance coefficient J_S based on ship speed ($J_S = V_S/nD$) in the following equation:

$$t = 0.0462 + 1.4741\, J_S + 0.0159\, J_S^2 - 3.2034\, J_S\, (P/D) + 1.8897\, J_S\, (P/D)^2$$

Then the following relationship was used to calculate ship ice resistance:

$$R_i = (T * (1 - t)) - R_{ow} \qquad (3.3\text{-}1)$$

where R_i = ice resistance; t = thrust deduction; T = total thrust; R_{ow} = open water resistance

Ice resistance and ship speed were then non-dimensionalized into the following terms:

$$\frac{R_i}{\rho g B h^2} \quad \text{and} \quad \frac{V}{\sqrt{gh}} \cdot \frac{(L/h)}{\sqrt{(B/h)}}$$

where ρ = mass density of sea water; B = ship maximum beam at waterline; g = gravitational acceleration; h = ice thickness in feet; L = length between perpendiculars; V = ship speed in feet/second

A first-degree linear regression analysis was performed on the data set to determine the coefficients C_0, C_2 for the equation

$$\frac{R_i}{\rho g B h^2} = C_0 + C_2 \frac{V}{\sqrt{gh}} \cdot \frac{(L/h)}{\sqrt{(B/h)}} \qquad (3.3\text{-}2)$$

The regression yielded $C_0 = 2.93868$ and $C_2 = 0.16349$ with a correlation of 94%. Both sides of Equation (3.3-2) were then multiplied through by $\rho g B h^2$ to give a dimensional equation which predicts ship resistance as a function of ice thickness and ship speed:

$$R_i = C_0 \rho g B h^2 + C_2 \rho g^{1/2} B^{1/2} L V h \qquad (3.3\text{-}3)$$

Figure 3.3 illustrates predicted ice resistance using Equation 3.3-3) for a range of ice thicknesses, along with all the level ice data points. In the following two sections of the report, data from the 1982 level ice resistance tests are given as well as a predictor equation based on the combined 1982 and 1984 data. Note that all data points were included in the regression analysis.

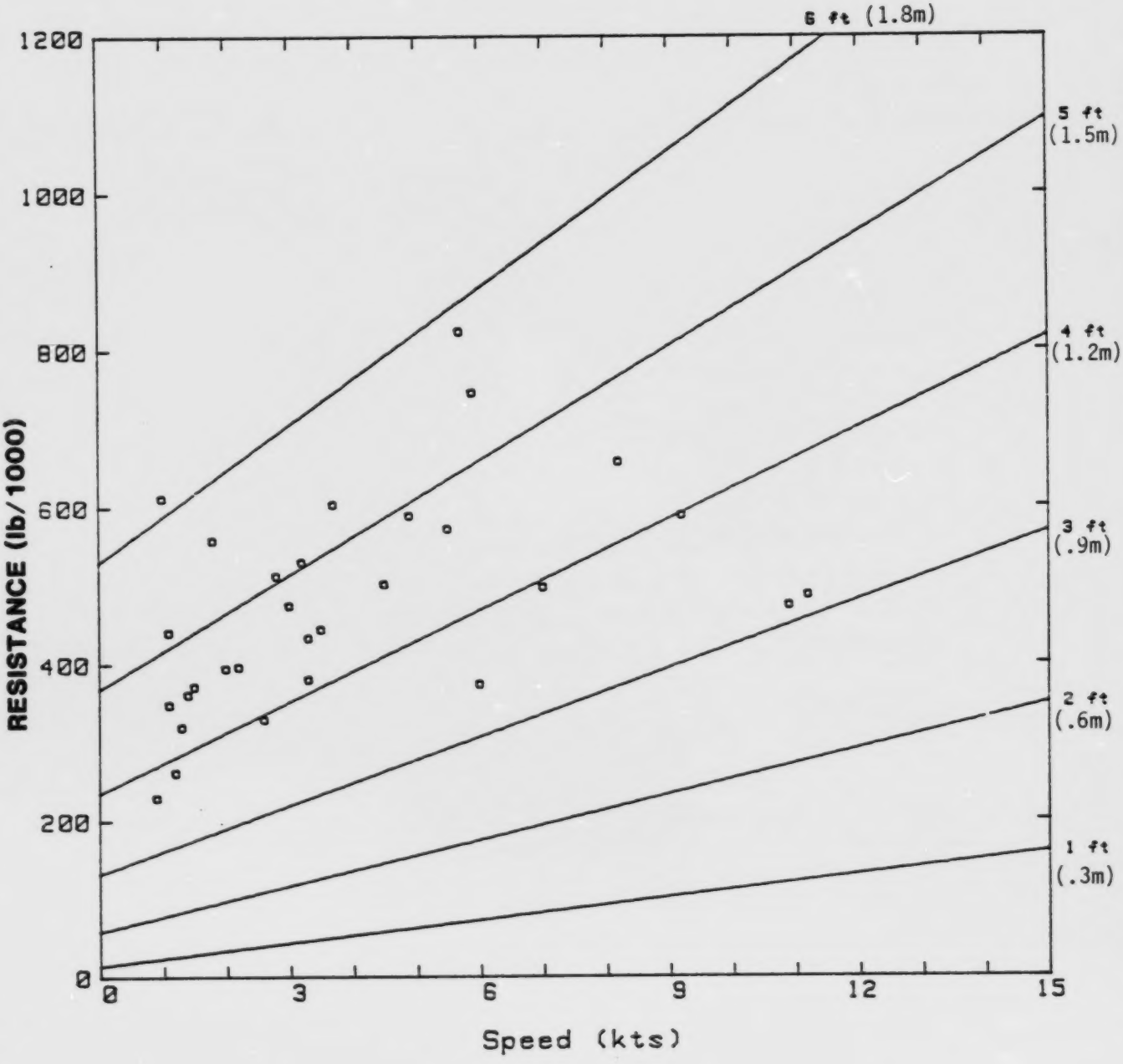


FIGURE 3.3

RESISTANCE PREDICTION
BASED ON 1984 DATA

3.4 Resistance Prediction Based on 1982 Data

Between April 4 and April 14, 1982, nineteen level ice resistance tests were conducted aboard POLAR STAR. A wide range of speeds, 0.5 to 14.3 knots, were obtained but the existing environmental conditions limited testing to ice that was never thicker than 1.6 feet (.49 m). From the nineteen tests, a total of 34 distinct level ice resistance data points were obtained as in Table 3.2 below. Figure 3.4 gives predicted ice resistance based on these data. Reference [3] provides a complete set of the raw data and analysis techniques employed.

TABLE 3.2
LEVEL ICE RESISTANCE DATA POINTS

TEST NO.	DATE	ICE THICKNESS (ft)(m)	AVERAGE SPEED (kts)	ICE RESISTANCE (lb)	SHAFT HORSEPOWER
001	4/4	0.6 .18	3.8	25,753	6,057
002	4/5	1.6 .49	0.8	97,413	6,610
003	4/5	1.6 .49	1.0	96,129	6,267
003	4/5	1.6 .49	1.4	78,530	6,153
004	4/5	1.6 .49	5.4	170,519	9,286
005	4/5	1.6 .49	10.0	304,398	18,486
005	4/5	1.6 .49	8.3	314,647	18,307
006	4/5	1.6 .49	0.6	97,981	6,238
006	4/5	1.6 .49	1.7	85,409	6,265
007	4/5	1.6 .49	1.4	94,205	6,305
007	4/5	1.6 .49	4.5	164,530	8.703
007	4/5	1.6 .49	3.7	200,062	9,058
008	4/5	1.6 .49	4.2	207,658	9,851
008	4/5	1.6 .49	10.3	218,664	15,532
009	4/5	1.6 .49	12.6	179,910	15,926
010	4/6	1.5 .46	0.7	54,698	5,360
011	4/6	1.5 .46	4.0	94,522	6,915
011	4/6	1.5 .46	7.3	109,111	8,018
012	4/6	1.5 .46	7.5	182,259	11,309
012	4/6	1.5 .46	8.6	203,946	11,930
013	4/6	1.5 .46	10.9	299,266	18,292
014	4/7	1.6 .49	6.1	180,663	9,730
014	4/7	1.6 .49	4.6	169,257	8,759
015	4/7	1.6 .49	14.3	274,855	23,504
016	4/12	1.3 .40	1.6	64,461	6,725
016	4/12	1.3 .40	4.8	103,442	8.493
016	4/12	1.3 .40	8.7	110,008	10,684
016	4/12	1.3 .40	3.2	102,360	7,366
016	4/12	1.3 .40	6.6	155,238	10,127
017	4/14	1.0 .30	1.4	32,782	6,157
017	4/14	1.0 .30	12.5	171,557	15,731
019	4/14	1.0 .30	8.5	104,074	8.454
019	4/14	1.0 .30	9.6	143,482	10,341
019	4/14	1.0 .30	6.7	124,413	7,886

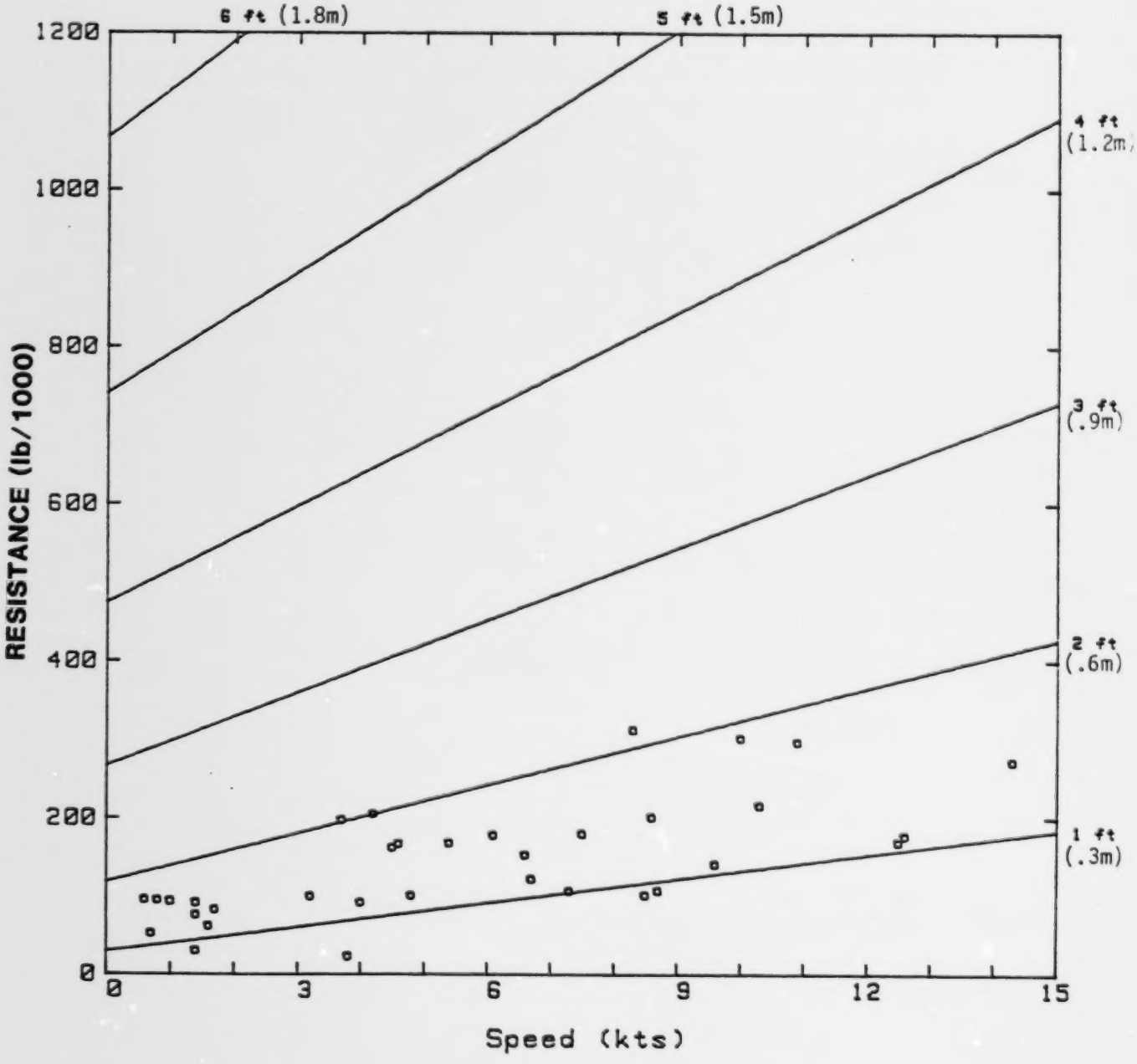


FIGURE 3.4

RESISTANCE PREDICTION
BASED ON 1982 DATA

3.5 Resistance Prediction Based on the Combined 1982 and 1984 Data

As illustrated in Section 3.3, the analysis techniques used for the 1984 data were exactly the same as were used in 1982. The nondimensional data, therefore, were compatible and a linear regression analysis was performed on the total of 64 data points. The coefficients in Equation (3.3-2) were determined to be $C_0 = 3.60373$ and $C_2 = 0.20013$ with a 92% correlation. The resulting equation for ice resistance is:

$$R_i = C_0 \rho g Bh^2 + C_2 \rho g^{1/2} B^{1/2} LVh.$$

Curves of ice resistance as a function of speed and ice thickness are shown in Figure 3.5 along with the measured data points from both the 1982 and 1984 test periods.

The predicted resistance from the combined data is higher than the actual measured resistance for the 1984 data, whereas the reverse is true for the 1982 data. In particular, the majority of the 1984 data was collected in ice which was between 4 and 5 feet (1.2 to 1.5 m) thick. The calculated ice resistance curve for 4 feet (1.2 m) ice thickness is shown to nearly bisect the bulk of the 1984 data. Conversely, the icebreaking resistance in 6 feet (1.8 m) of ice predicted by the 1982 data (data obtained in 1.6 ft (.49 m) thick ice) is drastically lowered.

A summary of the regression coefficients for the 1982, 1984, and combined data is shown in Table 3.3 below.

TABLE 3.3

	NUMBER OF DATA POINTS	COEFFICIENTS C_0	C_2	CORRELATION
1982 Data	34	5.92212	0.1734	87%
1984 Data	30	2.93868	0.16349	94%
Combined	64	3.60373	0.20013	92%

A line drawn through the higher velocity data points at each ice thickness would indicate the limiting icebreaking ability of the POLAR Class to be approximately 6 ft (1.8 m) at 3 knots. It therefore appears that the 64 data points from both years of testing give a good representation of the icebreaking resistance of the POLAR Class.

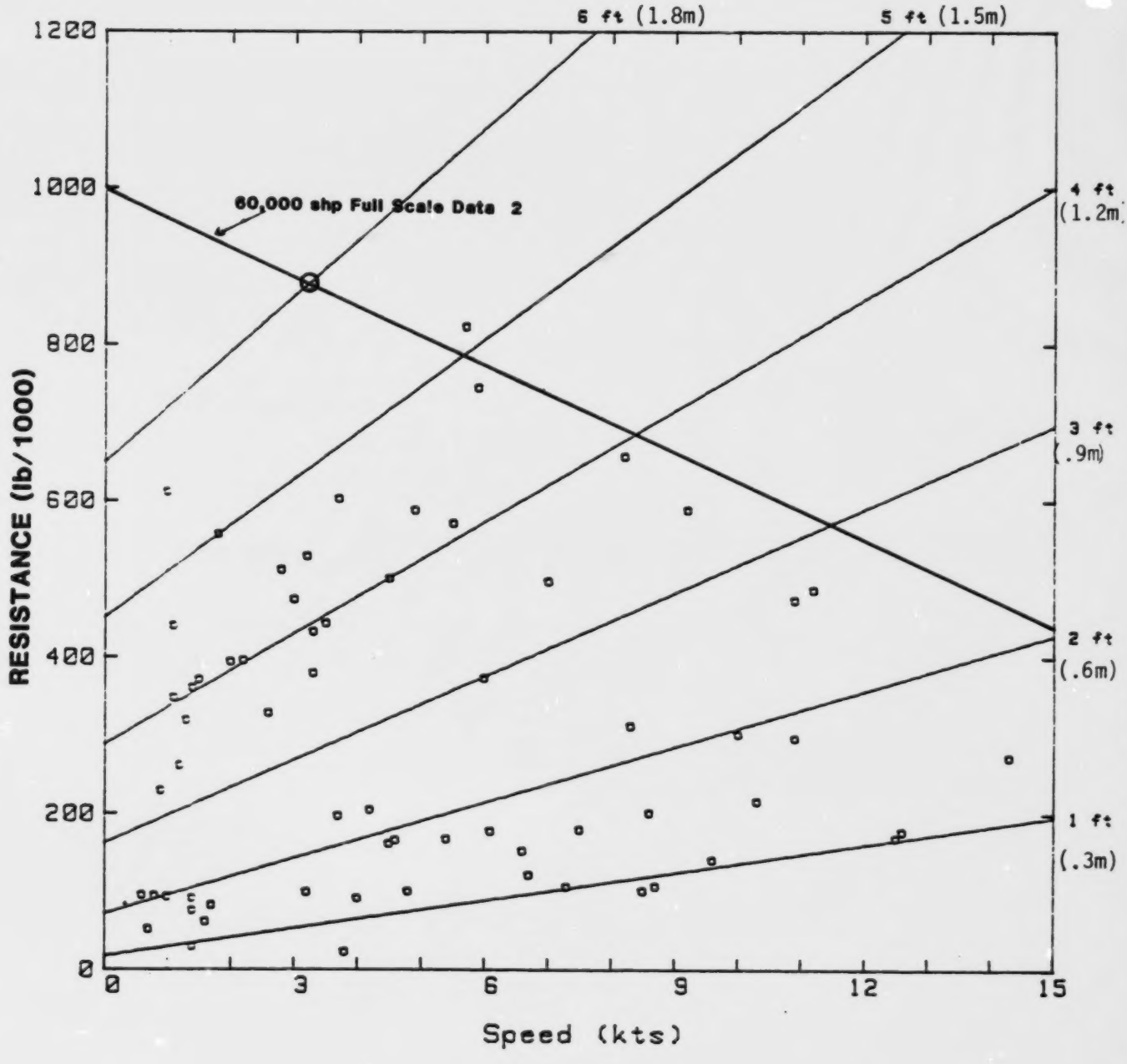


FIGURE 3.5

RESISTANCE PREDICTION
BASED ON 1982 & 1984 DATA COMBINED

3.6 Comparison with Ice Resistance Prediction Models

The results of the icebreaking resistance tests with the USCGC POLAR SEA have been compared with two ice resistance prediction models.

An evaluation of the semi-empirical ice resistance prediction model "RICE" is included in Appendix E. This model was the result of a major effort made during 1981-82 which was jointly supported by Transport Canada and the U.S. Maritime Administration and reported by J.W. Lewis, V. Bulat, I. Glen, and T. Kotras [4]. This comparative evaluation showed that, based on the measurements reported herein and the results obtained from running RICE, the field measurements are of the order of fifty percent higher than corresponding ice resistance predictions made by RICE. The latter were obtained for solid ice cover with snow cover and with no lateral pressure.

The development of the semi-empirical model RICE was based on resistance data of a limited number of ships, which did not include the USCGC POLAR SEA. Therefore, further investigation will be necessary to identify the possible causes for the deviations in resistance and adjust the semi-empirical model to account for any major differences in the breaking pattern and associated variables.

Follow-on work on the development of a resistance prediction model resulted in a more advanced model "SPLICE". This work was supported by the U.S. Coast Guard and is reported in [5]. An evaluation of this semi-empirical ice resistance prediction model is included in Appendix E. The model was updated to include the most recent experiences obtained from the full scale observations. The predictions obtained from running SPLICE showed a good correlation with the recent trial data, as illustrated in Figure 3.6. Seventy-five percent of the data lies within the ±25% correlation boundary, which may be considered good correlation for this type of measurement and prediction.

The model SPLICE is considered more advanced than the model RICE and it has been demonstrated that the present version of the former model provides a better prediction of the resistance in ice. The development of the model RICE provided the groundwork for the continued development into the model SPLICE. Although the model RICE has not been updated over the last few years, the work can be carried out, as suggested above, using all the additional resistance data that has become available since the initial development. However, it is recommended that further developments on ice resistance prediction models be carried out on the more advanced model SPLICE. Therefore it is suggested that the semi-empirical ice resistance prediction model SPLICE be acquired from U.S. Coast Guard and any further work, if required, be performed on this model.

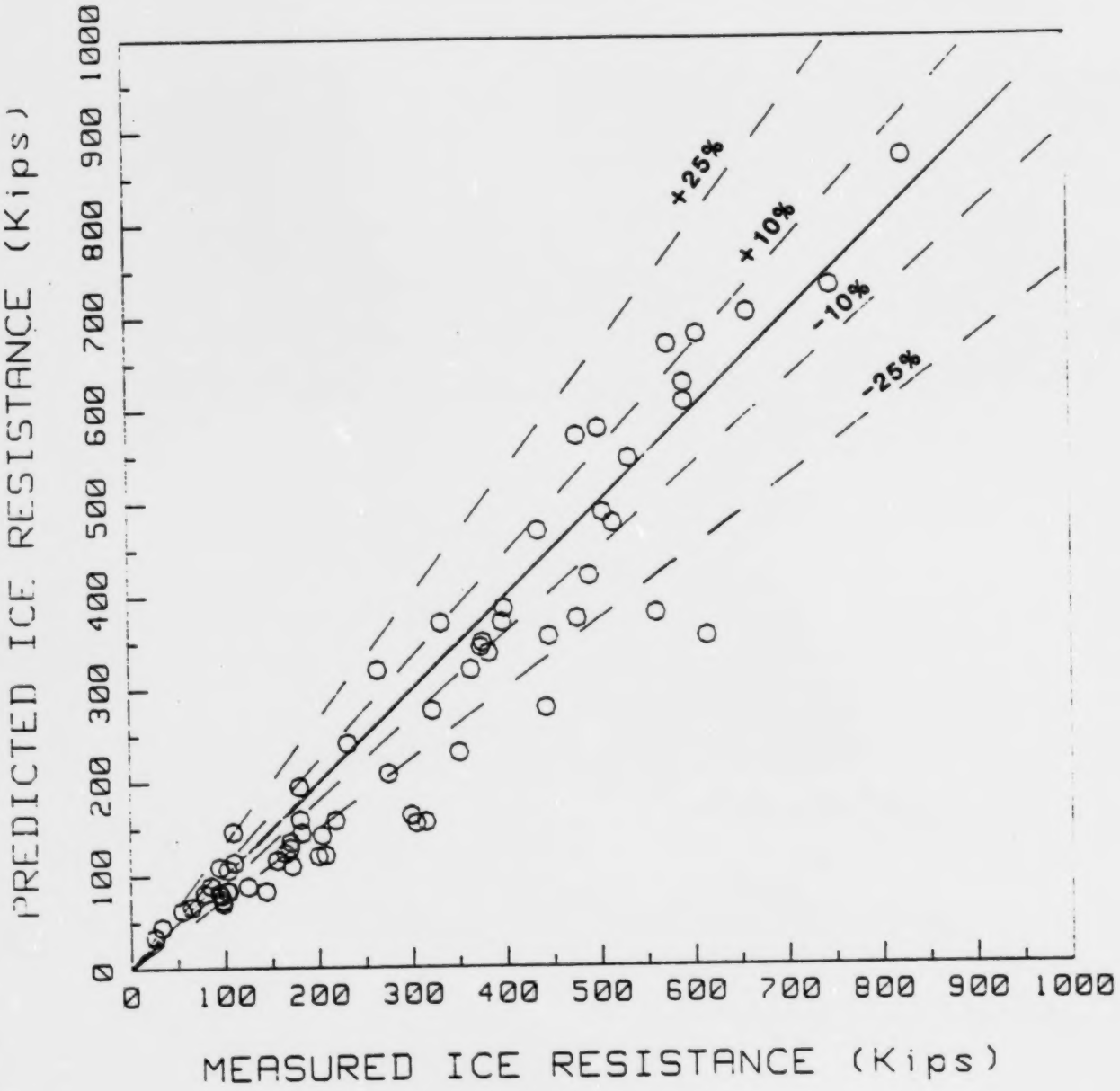


FIGURE 3.6 POLAR CLASS

4. OBSERVATIONS AND NOTES REGARDING THE 1984 DATA COLLECTION

4.1. POLAR SEA had expended considerable fuel prior to her arrival in McMurdo and the operating draft was 26'0" (7.9 m) forward and 28'0" (8.5 m) aft from January 9 to January 11. Thereafter the forward bow peak tank was ballasted and the draft was 27'0" (8.2 m) forward and 27'6" (8.4 m) aft. The effect of draft on icebreaking resistance is unknown particularly as it relates to a possible increase in propeller ice milling.

It is interesting to note that observed propeller-ice milling and the subsequent ship vibration is significantly less than on most of the Arctic deployments. Arctic operations require the POLAR Class to transit through pressure ridges in excess of the draft of the ship and also to break solid ice pieces in excess of 6 ft (1.8 m) (rafted and multiyear ice). As a result, the frequency and magnitude of ice milling in the Antarctic is considerably less than in the Arctic.

4.2 Winds were usually less than 15 knots and underwater currents, although unmeasured, are believed small. Both factors were therefore considered to have no significant effect on the ice resistance measurements.

4.3 During the start of the test program, the starboard pitch-setter was not functioning correctly. Propeller pitch in the pilot house was reading 15 to 25% higher than actual. It was observed that the ship would turn to starboard with equal propeller pitch on all shafts and rudder amidships. Usually the ship turns to port under normal circumstances. The pitch-setter was corrected and the test program continued. It is believed that the effect of this on the inital data points is within the expected accuracy of the measured data.

It should be noted that the pilot house has no method of knowing if the shafts are delivering equal horsepower or thrust during normal icebreaking operations. As such, the malfunctioning pitch-setter may have gone undetected for a longer time period were it not for the test program. Such shaft imbalances lead to icebreaking inefficiencies. Meters installed in the pilot house would aid balancing the propeller thrust on all shafts.

4.4 Testing with one type of prime mover on each of the three shafts is most desirable. This was infeasible during a portion of the test program due to a component malfunction on the gas turbine-reduction gear system. As a result, tests with a machinery configuration of GT/DD/GT resulted in the center shaft producing a negative thrust (effectively being dragged through the water). It should be noted that a 50% centerline pitch setting was also imposed during these tests, thus restricting full diesel horsepower from being developed. Since the thrust used in the calculation is total thrust over all three shafts, the effect is assumed to be taken into account in the presented data.

4.5 Near-zero velocity icebreaking resistance was difficult to obtain in thick ice. As the ship started from zero velocity, very large cusps would fail at the bow which allowed the ship to move forward in the

area vacated by the submerging ice piece. As the ship advanced and encountered solid ice again, the speed slowed to almost a stop and then accelerated as another cusp was broken. In effect, the starting resistance tests in thick ice (about 5 ft (1.5m)) resulted in velocity variations from 0.5 to 2.5 knots. In thin ice of 1.6 ft (.49m), a steady-state speed of 0.5 knots is obtainable. The speed used in the data reported in Section 3.2 is the average speed taken from a review of the time series data and is considered to be compatible with the average total resistance measured. An example of this low speed averaging from the time series data may be seen for test 001.1 on page B.4.

4.6. Although direct measurements of the channel width due to icebreaking were not made, some observations can be made. In thicker ice the average channel width was slightly greater than in thin ice at a speed of 5 knots; approximately 10-20 percent greater. It is also important to note that the channel behind the icebreaker was almost always filled with broken ice and that piece size varied greatly. Specifically, the size ranged from small chips to pieces as large as 40 ft by 10 ft (12.2 m by 3.0 m). The quantity of relatively large ice pieces was such that the ice profiling team walked across the broken ice channel immediately after the passage of the ship without difficulty.

4.7. From a testing point of view, operations in the Antarctic proved more than satisfactory. Actual shipboard testing required an average of 4 to 6 hours per day after which time the ice profiling team worked on the ice while the ship was preparing the channel for the resupply tanker. In effect, 75% of every day was still available for channel preparations. In addition, our primary test area was in the channel track proper so an absolute minimum of "added" icebreaking was required during the entire operation.

It is believed that testing in the Antarctic can be performed in about 25% of the time required in the Arctic because of available ice conditions, daylight, and the overall ease of performing operations on landfast ice (the ice in the Arctic is moving).

4.8. Measurement of ice impact loads on the instrumented bow panel did not interfere with the collection of ice resistance data. This system had an independent instrumentation and was demonstrated on two prior deployments. The ship's crew contributed greatly to the timely removal of the video boom from the cargo hold and its installation over the port bow. The system proved effective and valuable data was obtained.

5. RECOMMENDATIONS

5.1 Testing of the POLAR Class in the thick, level ice of Antarctica proved very successful. Good data sets of icebreaking resistance and ice impact loads on the instrumented bow panel were obtained and the conclusions have been presented at the beginning of the report. Should the opportunity again be available, the measurement of icebreaking motions (dynamics) in thick ice should be pursued. Experience in the Antarctic has clearly demonstrated the need to incorporate icebreaking dynamics in the more sophisticated models. However, field data is currently lacking on ship behaviour in thick, level ice and analytic models are incapable of verification or enhancement. The Antarctic provides a unique opportunity to collect this data.

5.2 With the advent of unconventional bow forms (spoon-shaped, WAAS), there is an increasing need to determine the effect of bow shape on maneuverability. Yet the maneuvering characteristics of the POLAR Class are not well understood or documented. Continued trials to measure thick ice turning performance are needed. Concurrently, propeller-ice milling torque (magnitude and frequency) for straight ahead and turning operations could be documented and used in fatigue analysis of propeller components as well as hull structure.

5.3 A comparison of Antarctic and Arctic sea ice has been based on salinity-temperature profiles to infer flexural ice strength. The comparison appears favourable based on the result from this year's testing. In addition to the collection of more salinity-temperature data from ice cores, further comparison of Antarctic and Arctic sea ice is possible with unconfined, uniaxial compression tests or Brazil tests (flexural strength). About 100 samples would be desired to give statistical significance to the results. In a six foot core length, about ten, six inch samples could be cut for compression testing and about twenty samples for Brazil tests. In addition to these tests, a crystallographic analysis would reveal the internal structure of the Antarctic sea ice in the test area for further comparison with Arctic sea ice.

5.4 Based on the operating experience gained, the remaining priority 2 and 3 test objectives of the 1984 program could and should be achieved during a future deployment provided that adequate time and resources are applied, and the full cooperation of the ship is gained. Specifically, data on cusp size and channel width can be performed by the ice profiling team while the ship continues to prepare the channel for the resupply tanker. In addition, parallel track level ice resistance can be conducted concurrently with the channel break-in. Furthermore, broken ice channel resistance can be performed in a minimum of time. In effect, a well defined test program could be integrated with other shipboard operational requirements as accomplished this year.

5.5 Suggestions for improvement in test operations were made by test team members. Among them are:

1. The small red numbered marking flags were sometimes lost because of snow drifting. To improve the visibility and reduce the chance of snow covering them, it is recommended that a ski pole type basket or three prong basket be attached to the top of the flag staff in order to lift it off the ice at the flag end for better visibility.

2. As a double check on shaft horsepower, it would be a good idea if personnel were available to record, in main control, the generator output in megawatts while operating on all diesels.

5.6 It is recommended that the semi-empirical ice resistance prediction model SPLICE be acquired by the Transportation Development Centre from USCG for future developments in the area of ice resistance prediction models.

6. REFERENCES - CITED

1. Voelker, R.P., "Preliminary Test Plan for Antarctic Level Ice Resistance Tests of USCGC POLAR SEA", Arctec, Incorporated Report No. 872C-1, Columbia, MD., September 1983.

2. DeBord, F. W., et al, "Winter 1981 Trafficability Tests of the USCGC POLAR SEA, Volume V, Bollard and Tow-Rope Pull Tests", Arctec, Incorporated, Report No. 583C-3, Columbia, MD. December 1981.

3. Geisel, F.A., et al, "Arctic Deployment of USCGC POLAR STAR-Winter 1982, Volume III, Polar Class Performance: Trafficability, Level Ice, and Pressure Ridges", Arctec Incorporated Report No. 772C, Columbia, MD., November 1982.

4. Lewis, J.W. Bulat, V., Glen, I.F., Kotras, T., "A Semi-Empirical Ice Resistance Model, Volumes I and II", ACL Report FR444C-4, April 1983.

5. Kotras, T., "Development of a Model for Predicting Ship Resistance in Level Ice", Arctec Incorporated Report No. 583-E, submitted to USCG, 29 October 1982.

6. Daley, C., Brown, R., St.John, J., Myers, J., "Polar Class Antarctic 1984 - Ice Impact Tests, prepared for Transportation Development Centre, TP7184E,March 1985.

REFERENCES - UNCITED

7. Lecourt, E.J. and P.C. Deslauriers, "Icebreaking Model Tests of the USCGS POLAR STAR", Arctec Incorporated Report No. 278C-2, Columbia, MD. 1976.

8. McIntosh, J.A., "A Tentative Calculation of Icebreaking Resistance of the USCGC POLAR STAR", SNAME (Ice Tech 81), Ottawa, Canada, June 1981.

9. Welsh, R.P. (ed)., "Test and Evaluation of USCGC POLAR STAR WAGM 10, Volume I through IV", Naval Ocean Research and Development Activity, NSTL Station, MS, September 1978.

APPENDIX A

ICE CORE DATA AND ESTIMATES OF FLEXURAL STRENGTH

This appendix presents the measured salinity and temperatures and presents the calculation of flexural strength.

Flexural strength was calculated using the formulation by Vaudrey [*]

$$\text{VAUDREY:} \quad \sigma_f = 960\,[1 - 0.063\,\sqrt{\nu}] \quad \text{kPa}$$

where σ_f is the flexural strength in kPa, and ν is the brine volume content in parts per thousand.

The brine volume content was calculated using the method of Frankenstein and Garner [**]; that is,

$$\nu = S\left[\frac{52.56}{\theta} - 2.28\right] \quad \text{for } 0.5 \leq \theta \leq 2.06$$

$$\nu = S\left[\frac{45.917}{\theta} + .930\right] \quad \text{for } 2.06 < \theta \leq 8.2$$

$$\nu = S\left[\frac{43.795}{\theta} + 1.189\right] \quad \text{for } 8.2 < \theta \leq 22.9$$

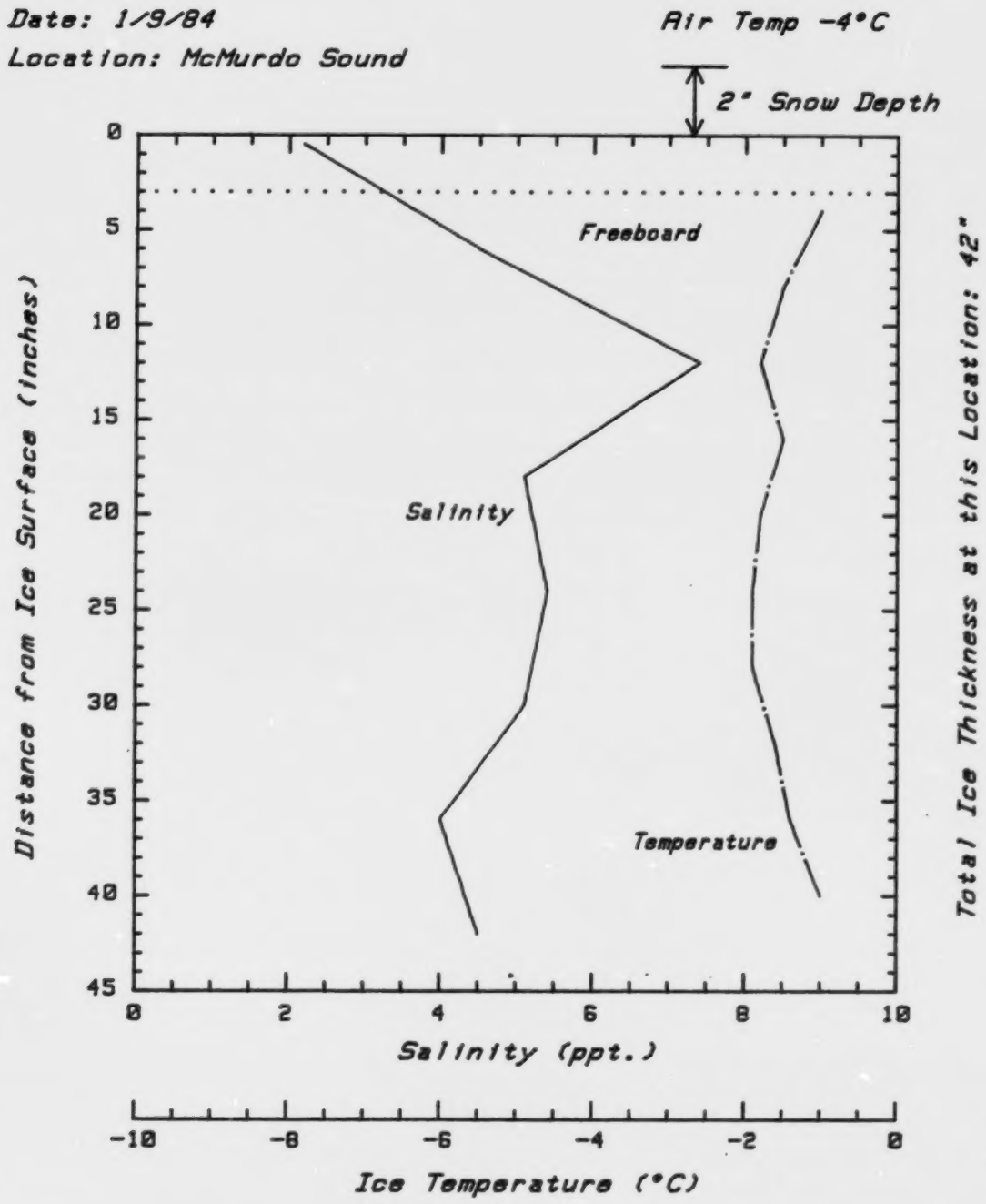
where S is the ice salinity in parts per thousand, and θ is the absolute value of the ice temperature in degrees centigrade.

A flexural strength is calculated at each depth where either a salinity or a temperature was physically measured (missing values are determined by linear interpolation). Core No. 1 gave half the flexural ice strength of Core No. 2, which was only a few feet away. As a result, Core No. 1 was determined to be suspect. Core No. 6 was also considered suspect as ice temperatures from the core were above the freezing point of ice even though the instrumentation was calibrated before the measurements. Using the other ice cores, it is believed that a fair representation of the flexural ice strength is 44 psi (303.4 kPA).

---

* Vaudrey, K.D., "Ice Engineering--Study of Related Properties of Floating Sea-Ice Sheets and Summary of Elastic and Viscoelastic Analyses," Civil Engineering Laboratory, Naval Construction Battalion Center Report No. TR-860, December 1977.

** Frankenstein, G. and R. Garner, "Linear Relationship of Brine Volume and Temperature from -0.5°C for Sea Ice of 1% Salinity", U.S. Army CRREL Report, December 1966.



Salinity-Temperature Profile Core No. 001
Antarctic Ice Resistance Testing

Salinity-Temperature Profile Core No. 001
Antarctic Ice Resistance Testing

Date: 1/9/84
Location: McMurdo Sound

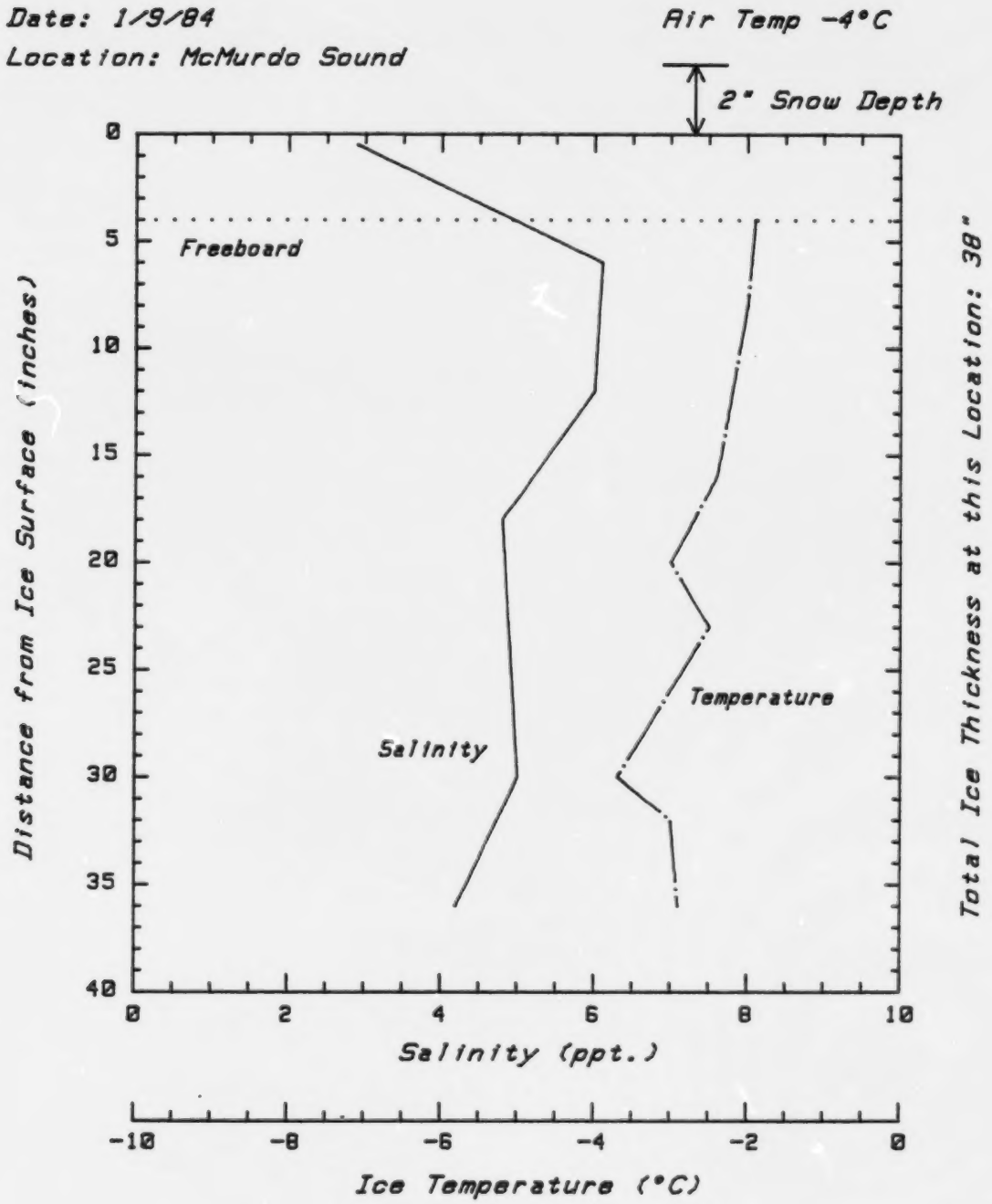
Air Temp -4°C
Snow Depth 2"
Freeboard 3"
Total Ice Thickness 42"

Distance from Ice Surface (inches)	Salinity (ppt.)	Temperature (°C)
0 .5	2.20	
4.0		-1.0
6.0	4.50	
8.0		-1.5
12.0	7.40	-1.8
16.0		-1.5
18.0	5.10	
20.0		-1.8
24.0	5.40	-1.9
28.0		-1.9
30.0	5.10	
32.0		-1.6
36.0	4.00	-1.4
40.0		-1.0
42.0	4.50	

Note: Calculated Ice Properties Based on Upper 75% of Ice Core.

Flexural Strength:

Vaudrey Formula:	27.2 psi	(187.6 kPa)
Lane Formula:	9.4 psi	(64.5 kPa)
Weeks & Assur Formula:	10.5 psi	(72.4 kPa)



Salinity-Temperature Profile Core No. 002
Antarctic Ice Resistance Testing

Salinity-Temperature Profile Core No. 002
Antarctic Ice Resistance Testing

Date: 1/9/84
Location: McMurdo Sound

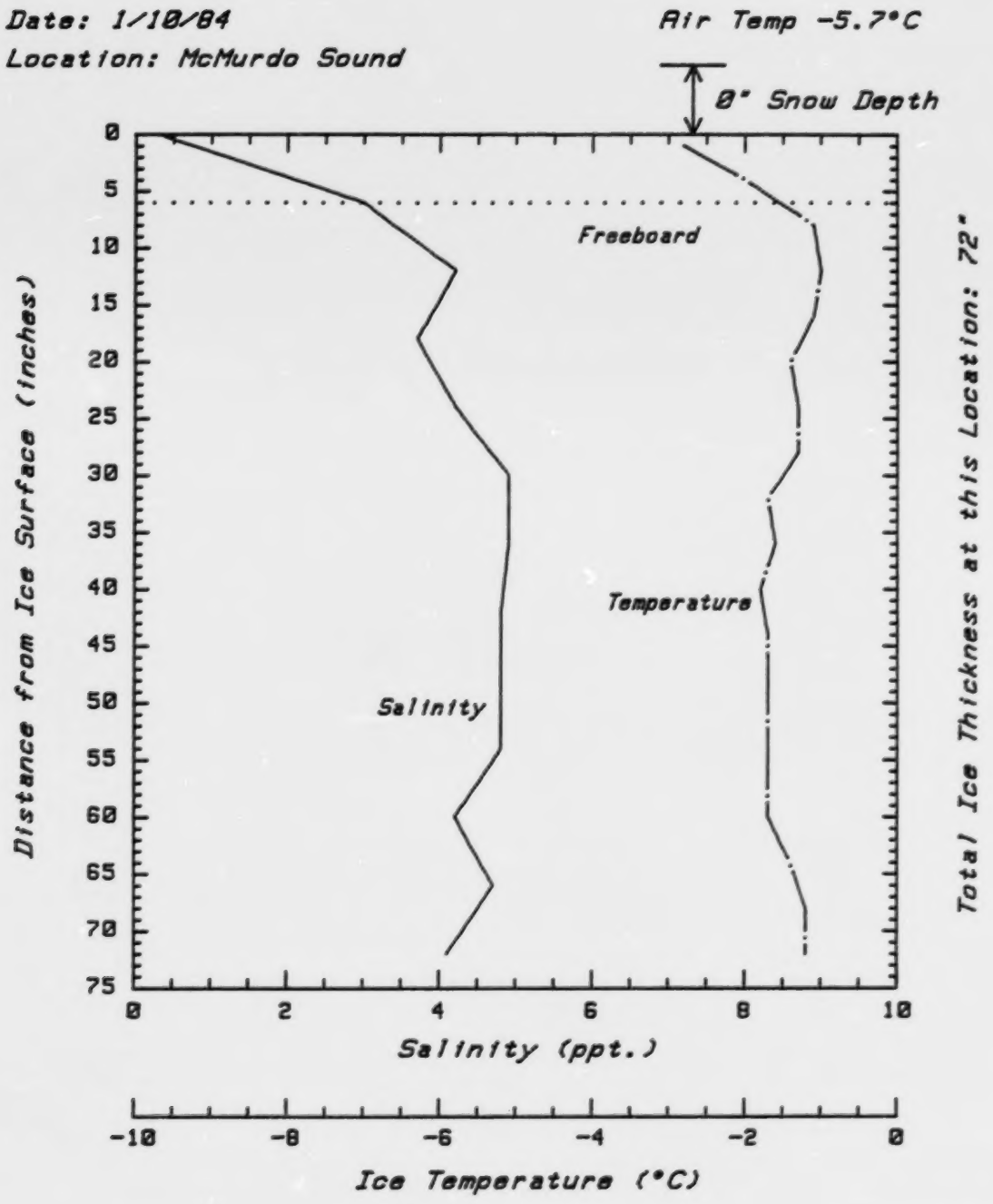
Air Temp -4°C
Snow Depth 2"
Freeboard 4"
Total Ice Thickness 38"

Distance from Ice Surface (inches)	Salinity (ppt.)	Temperature (°C)
0 .5	2.90	
4.0		-1.9
6.0	6.10	
8.0		-2.0
12.0	6.00	-2.2
16.0		-2.4
18.0	4.80	
20.0		-3.0
23.0		-2.5
24.0	4.90	
30.0	5.00	-3.7
32.0		-3.0
36.0	4.20	-2.9

Note: Calculated Ice Properties Based on Upper 75% of Ice Core.

Flexural Strength:

Vaudrey Formula:	48.3 psi	(333.4 kPa)
Lane Formula:	31.3 psi	(215.9 kPa)
Weeks & Assur Formula:	29.0 psi	(199.8 kPa)



Salinity-Temperature Profile Core No. 003
Antarctic Ice Resistance Testing

Salinity-Temperature Profile Core No. 003
Antarctic Ice Resistance Testing

Date: 1/10/84
Location: McMurdo Sound

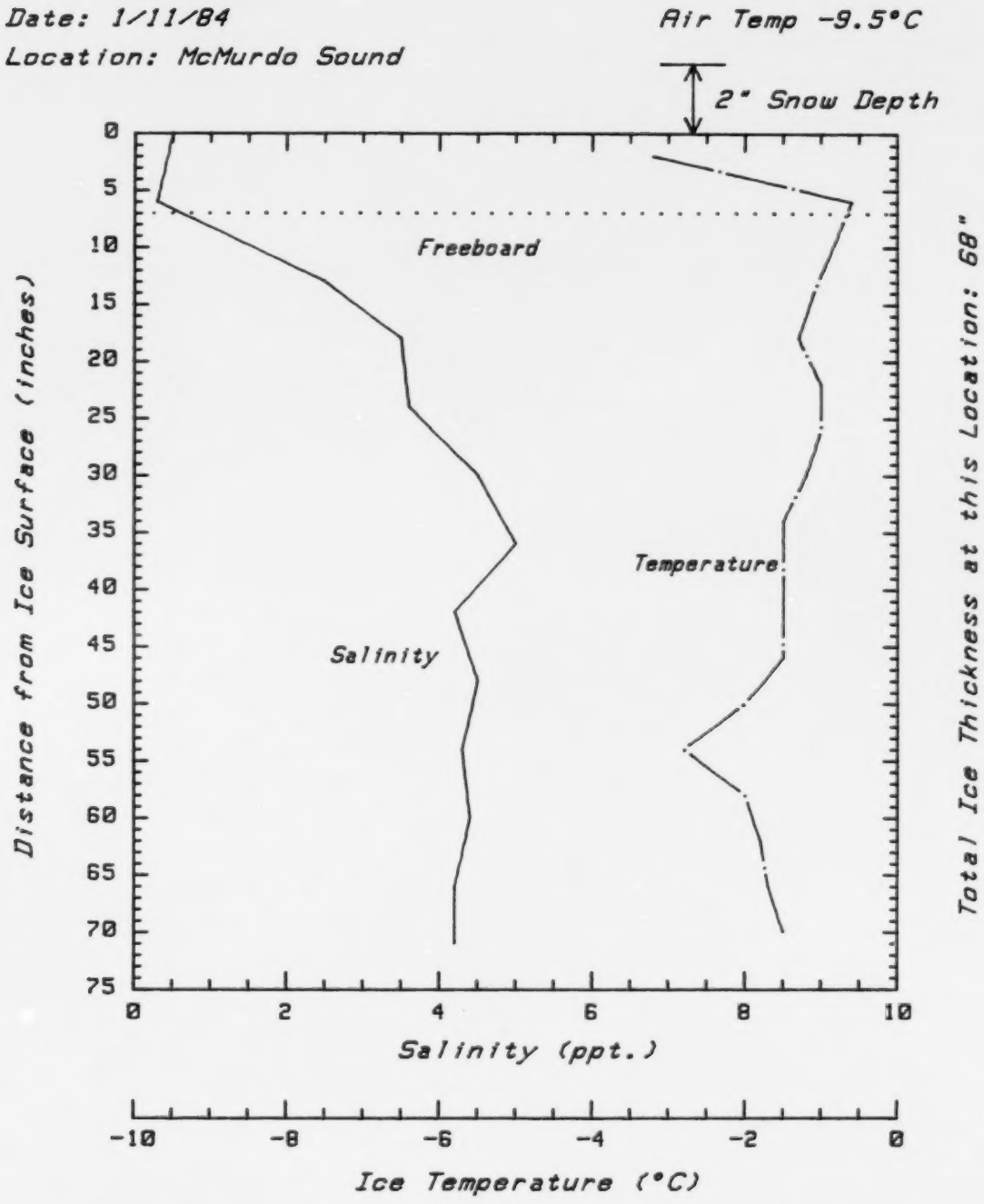
Air Temp -5.7°C
Snow Depth 0"
Freeboard 6"
Total Ice Thickness 72"

Distance from Ice Surface (inches)	Salinity (ppt.)	Temperature (°C)
0.0	0.30	
1.0		-2.8
4.0		-2.0
6.0	3.00	
8.0		-1.1
12.0	4.20	-1.0
16.0		-1.1
18.0	3.70	
20.0		-1.4
24.0	4.20	-1.3
28.0		-1.3
30.0	4.90	
32.0		-1.7
36.0	4.90	-1.6
40.0		-1.8
42.0	4.80	
44.0		-1.7
48.0	4.80	-1.7
52.0		-1.7
54.0	4.80	
56.0		-1.7
60.0	4.20	-1.7
64.0		-1.4
66.0	4.70	
68.0		-1.2
72.0	4.10	-1.2

Note: Calculated Ice Properties Based on Upper 75% of Ice Core.

Flexural Strength:

Vaudrey Formula:	37.4 psi	(258.0 kPa)
Lane Formula:	20.2 psi	(139.6 kPa)
Weeks & Assur Formula:	19.6 psi	(135.3 kPa)



Salinity-Temperature Profile Core No. 004
Antarctic Ice Resistance Testing

Salinity-Temperature Profile Core No. 004
Antarctic Ice Resistance Testing

Date: 1/11/84
Location: McMurdo Sound

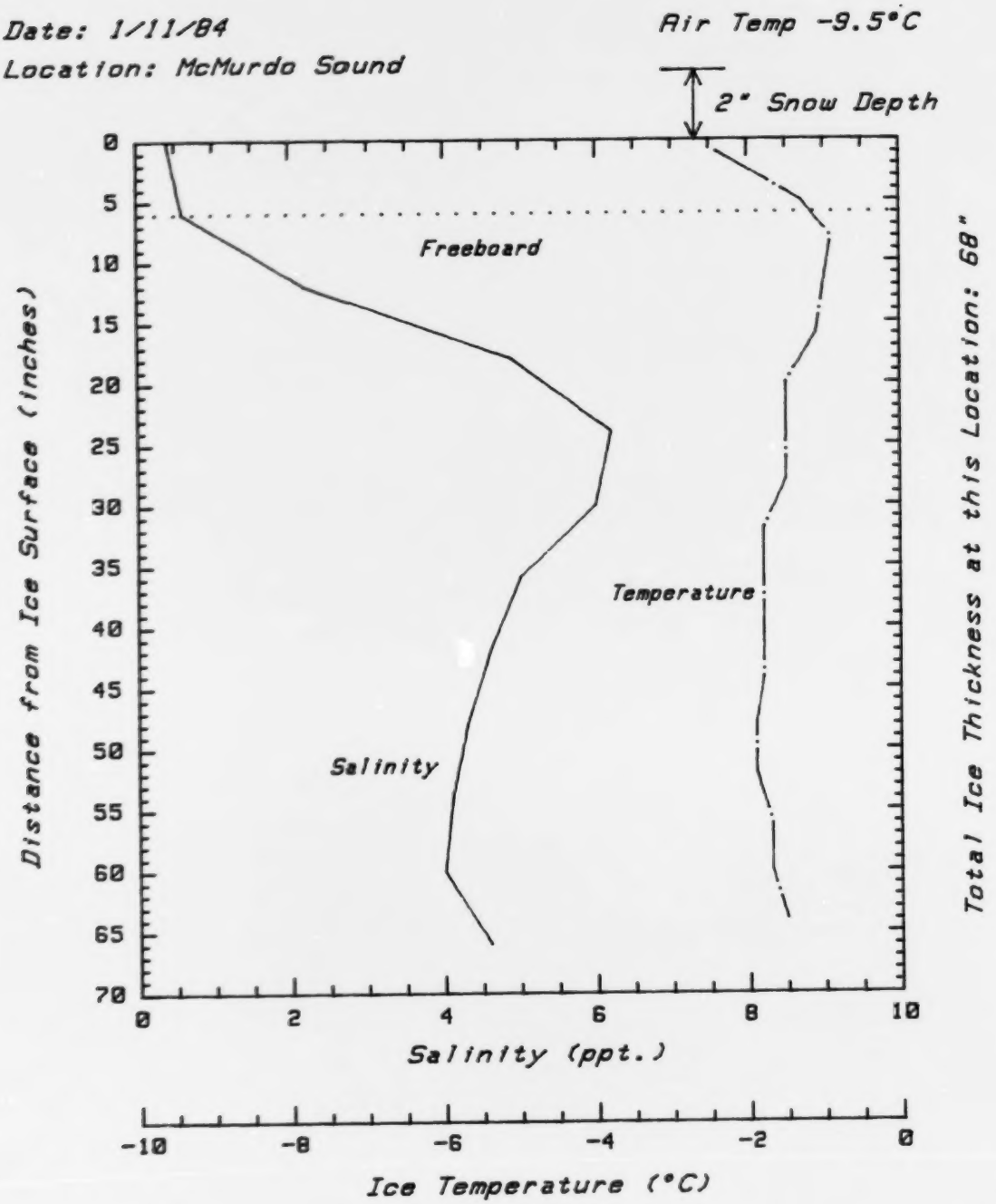
Air Temp -9.5°C
Snow Depth 2"
Freeboard 7"
Total Ice Thickness 68"

Distance from Ice Surface (inches)	Salinity (ppt.)	Temperature (°C)
0.0	0.50	
2.0		-3.2
6.0	0.30	-.60
13.0	2.50	
14.0		-1.1
18.0	3.50	-1.3
22.0		-1.0
24.0	3.60	
26.0		-1.0
30.0	4.50	-1.2
34.0		-1.5
36.0	5.00	
38.0		-1.5
42.0	4.20	-1.5
46.0		-1.5
48.0	4.50	
50.0		-2.0
54.0	4.30	-2.8
58.0		-2.0
60.0	4.40	
62.0		-1.8
66.0	4.20	-1.7
70.0		-1.5
71.0	4.20	

Note: Calculated Ice Properties Based on Upper 75% of Ice Core.

Flexural Strength:

Vaudrey Formula:	45.8 psi	(315.9 kPa)
Lane Formula:	28.8 psi	(198.2 kPa)
Weeks & Assur Formula:	26.8 psi	(184.8 kPa)



Salinity-Temperature Profile Core No. 005
Antarctic Ice Resistance Testing

Salinity-Temperature Profile Core No. 005
Antarctic Ice Resistance Testing

Date: 1/11/84
Location: McMurdo Sound

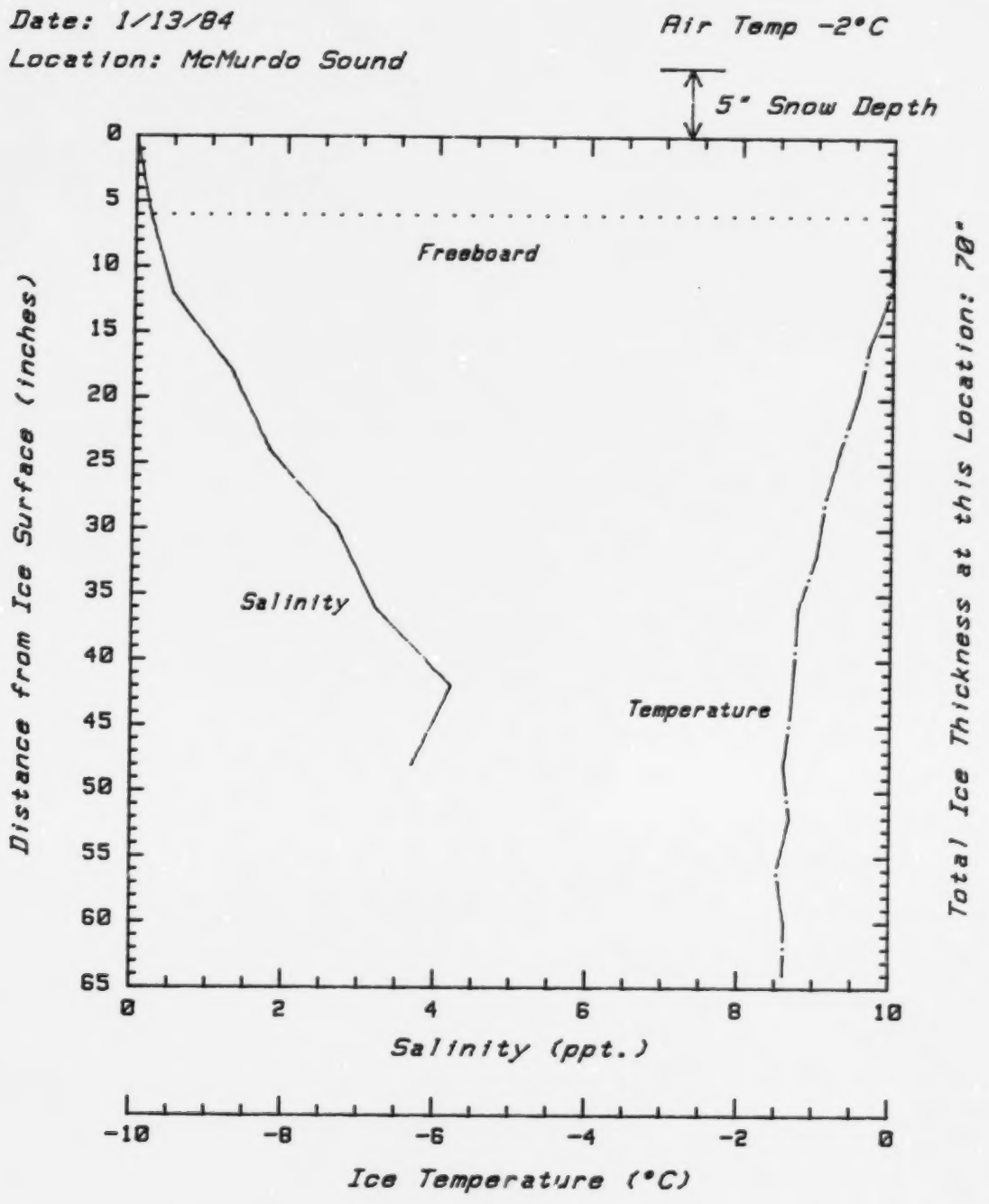
Air Temp -9.5°C
Snow Depth 2"
Freeboard 6"
Total Ice Thickness 68"

Distance from Ice Surface (inches)	Salinity (ppt.)	Temperature (°C)
0.0	0.40	
1.0		-2.4
5.0		-1.3
6.0	0.60	
8.0		-.90
12.0	2.20	-1.0
16.0		-1.1
18.0	4.90	
20.0		-1.5
24.0	6.20	-1.5
28.0		-1.5
30.0	6.00	
32.0		-1.8
36.0	5.00	-1.8
40.0		-1.8
42.0	4.60	
44.0		-1.8
48.0	4.30	-1.9
52.0		-1.9
54.0	4.10	
56.0		-1.7
60.0	4.00	-1.7
64.0		-1.5
66.0	4.60	

Note: Calculated Ice Properties Based on Upper 75% of Ice Core.

Flexural Strength:

Vaudrey Formula:	44.2 psi	(304.5 kPa)
Lane Formula:	27.1 psi	(186.7 kPa)
Weeks & Assur Formula:	25.4 psi	(175.1 kPa)



Salinity-Temperature Profile Core No. 006
Antarctic Ice Resistance Testing

Salinity-Temperature Profile Core No. 006
Antarctic Ice Resistance Testing

Date: 1/13/84
Location: McMurdo Sound

Air Temp -2°C
Snow Depth 5"
Freeboard 6"
Total Ice Thickness 70"

Distance from Ice Surface (inches)	Salinity (ppt.)	Temperature (°C)
0.0	0000	
1.0		-.01
4.0		-.01
6.0	0.20	
8.0		-.03
12.0	0.50	-.04
16.0		-.31
18.0	1.30	
20.0		-.46
24.0	1.80	-.69
28.0		-.88
30.0	2.70	
32.0		-.98
36.0	3.20	-1.22
40.0		-1.26
42.0	4.20	
44.0		-1.31
48.0	3.70	-1.4
52.0		-1.32
56.0		-1.48
60.0		-1.38
64.0		-1.39

Note: Calculated Ice Properties Based on Upper 75% of Ice Core.

Flexural Strength:

Vaudrey Formula:	33.5 psi	(231.0 kPa)
Lane Formula:	16.3 psi	(112.3 kPa)
Weeks & Assur Formula:	16.3 psi	(112.2 kPa)

APPENDIX B

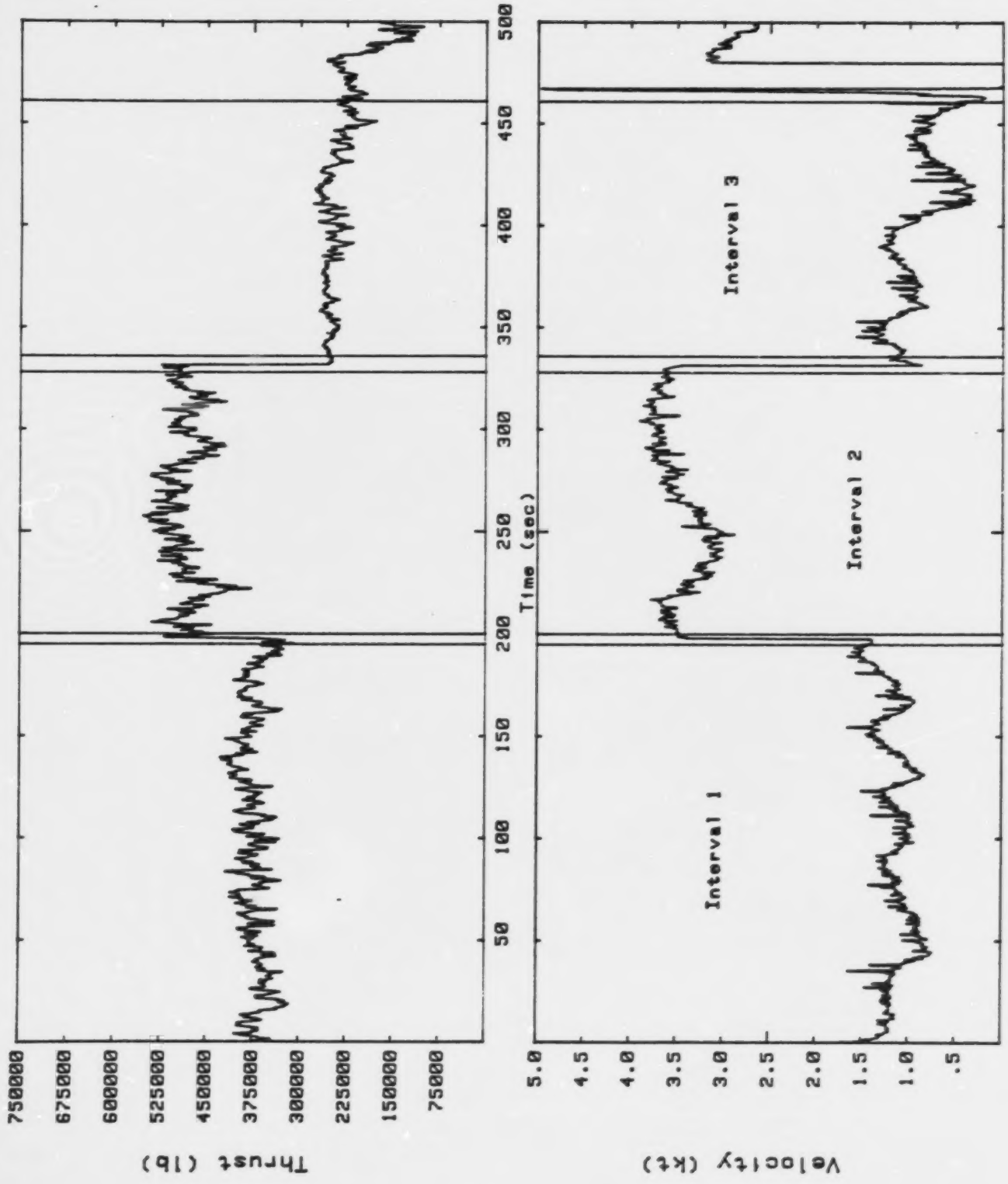
1984 POLAR SEA RESISTANCE DATA

This appendix presents all the recorded parameters from the test program.

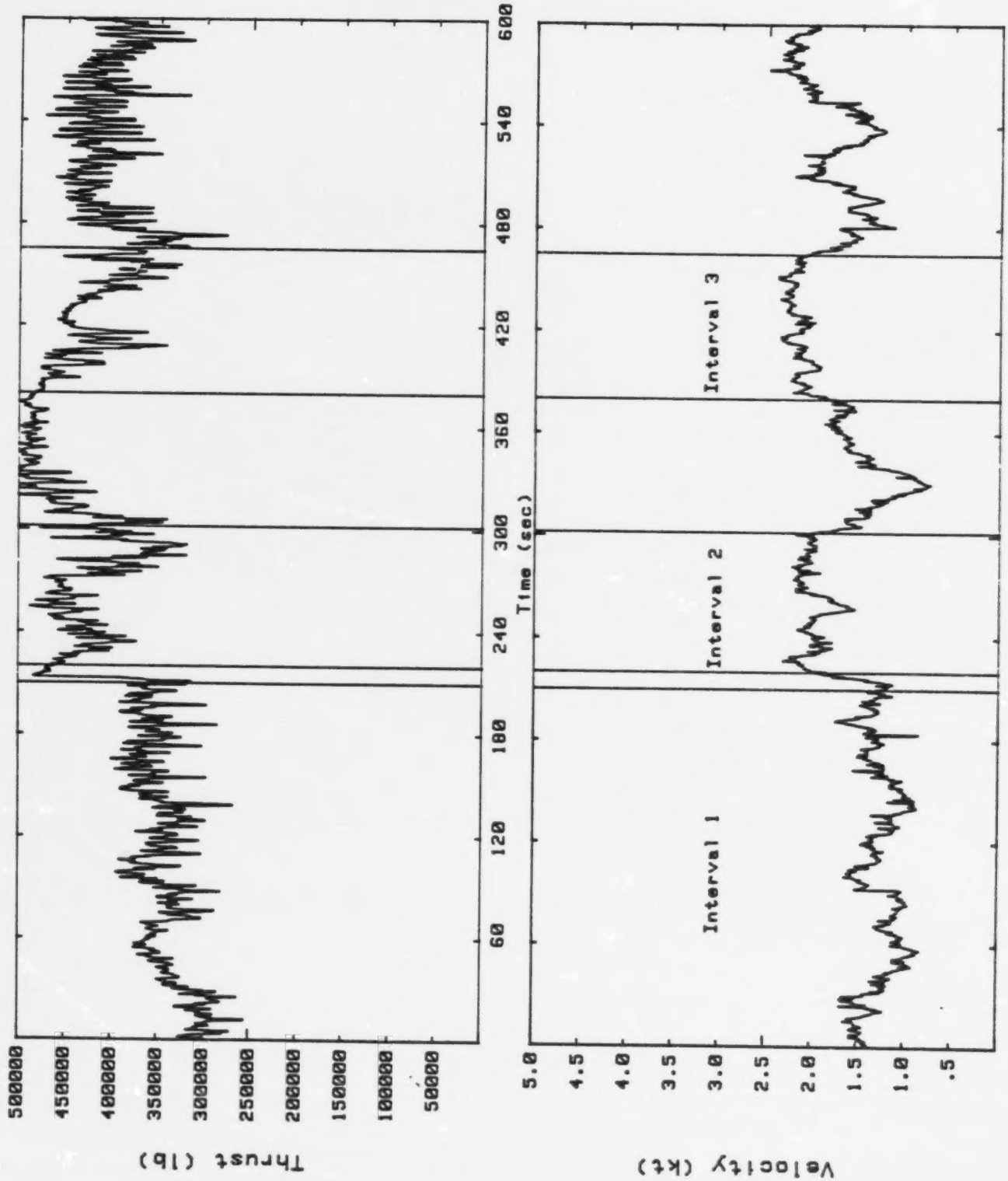
TEST NUMBER	DATE	TIME INTERVAL (sec)	AVERAGE SPEED (kts)	TOTAL AVERAGE THRUST (lb)	CALCULATED AVERAGE SHAFT HORSEPOWER
001.1	1/9	0-190	1.1	373,819	11,308
001.2	1/9	200-325	3.5	488,244	19,229
001.3	1/9	335-460	0.9	247,808	14,190
002.1	1/10	0-210	1.3	343,611	13,675
002.2	1/10	220-305	2.0	424,064	17,379
002.3	1/10	380-465	2.2	425,911	16,263
003.1	1/10	265-385	1.4	388,535	23,597
003.2	1/10	0-280	3.3	475,344	30,113
003.3	1/10	390-590	4.9	643,603	38,717
004.1	1/10	0-270	5.9	819,225	51,225
005.2	1/11	85-405	1.5	399,751	25,793
005.3	1/11	450-640	3.0	514,608	35,251
005.4	1/11	650-810	3.2	574,655	35,460
006.1	1/11	40-180	3.7	654,044	38,915
007.1	1/12	290-440	5.7	902,082	57,400
008.1	1/12	0-125	8.2	745,784	51,342
008.2	1/12	125-250	2.8	557,346	31,513
008.3	1/12	260-400	4.5	555,915	35,604
008.4	1/12	0-200	9.2	679,277	49,804
008.5	1/12	275-345	11.0	564,521	42,516
008.6	1/12	360-475	11.2	586,654	42,615
009.1	1/13	200-500	1.0	654,058	18,251
010.1	1/13	0-245	1.2	281,304	19,517
011.1	1/13	20-270	5.5	631,563	38,669
011.2	1/13	275-595	1.2	473,000	19,129
011.3	1/13	160-485	1.8	601,925	22,290
012.1	1/13	0-170	2.6	362,778	24,617
013.1	1/13	0-125	7.0	564,469	34,729
013.2	1/13	185-420	3.3	423,793	21,700
013.3	1/13	425-645	6.0	420,510	29,801

AVERAGE TORQUE (ft-lb)			RPM			PROPELLER PITCH (%)		
P	C	S	P	C	S	P	C	S
135,370	199,766	62,607	128	173	128	50	31	60
215,209	328,996	126,727	130	173	130	64	55	67
177,904	218,782	101,696	131	173	131	53	34	50
200,061	206,720	148,379	127	131	127	55	61	58
252,039	259,562	191,137	128	131	128	64	71	71
260,828	233,243	169,129	127	129	127	65	69	73
296,861	286,464	166,330	160	175	160	53	52	47
389,103	343,219	227,688	160	174	160	64	61	58
425,204	440,461	367,881	160	174	160	69	72	87
576,123	554,437	410,553	158	171	158	84	91	85
258,853	309,380	253,532	160	173	160	48	55	54
399,505	393,643	333,041	160	173	160	65	66	60
477,855	302,994	359,923	160	174	160	73	55	68
460,748	441,775	339,074	160	174	160	74	70	67
601,546	695,870	553,702	158	170	158	87	92	92
568,061	616,040	453,333	159	174	159	85	89	86
348,631	328,256	330,024	160	174	160	54	58	62
417,213	357,858	364,139	160	174	160	65	63	62
521,448	625,715	437,193	160	174	160	84	91	87
426,949	581,798	335,222	160	174	160	84	91	84
422,174	582,918	343,924	160	174	160	85	92	88
210,088	198,102	229,079	160	130	160	43	56	42
291,134	184,642	200,431	160	130	160	54	54	45
590,428	183,633	539,074	158	130	158	84	59	88
198,323	176,435	287,137	160	130	160	39	49	55
351,655	180,014	234,998	160	130	160	63	50	43
367,109	179,632	296,971	160	130	160	62	50	43
513,549	170,256	491,366	160	130	160	84	55	87
296,870	203,645	251,176	160	130	160	58	54	42
407,910	189,576	422,432	159	130	159	74	56	75

TEST NUMBER 001, January 10, 1983

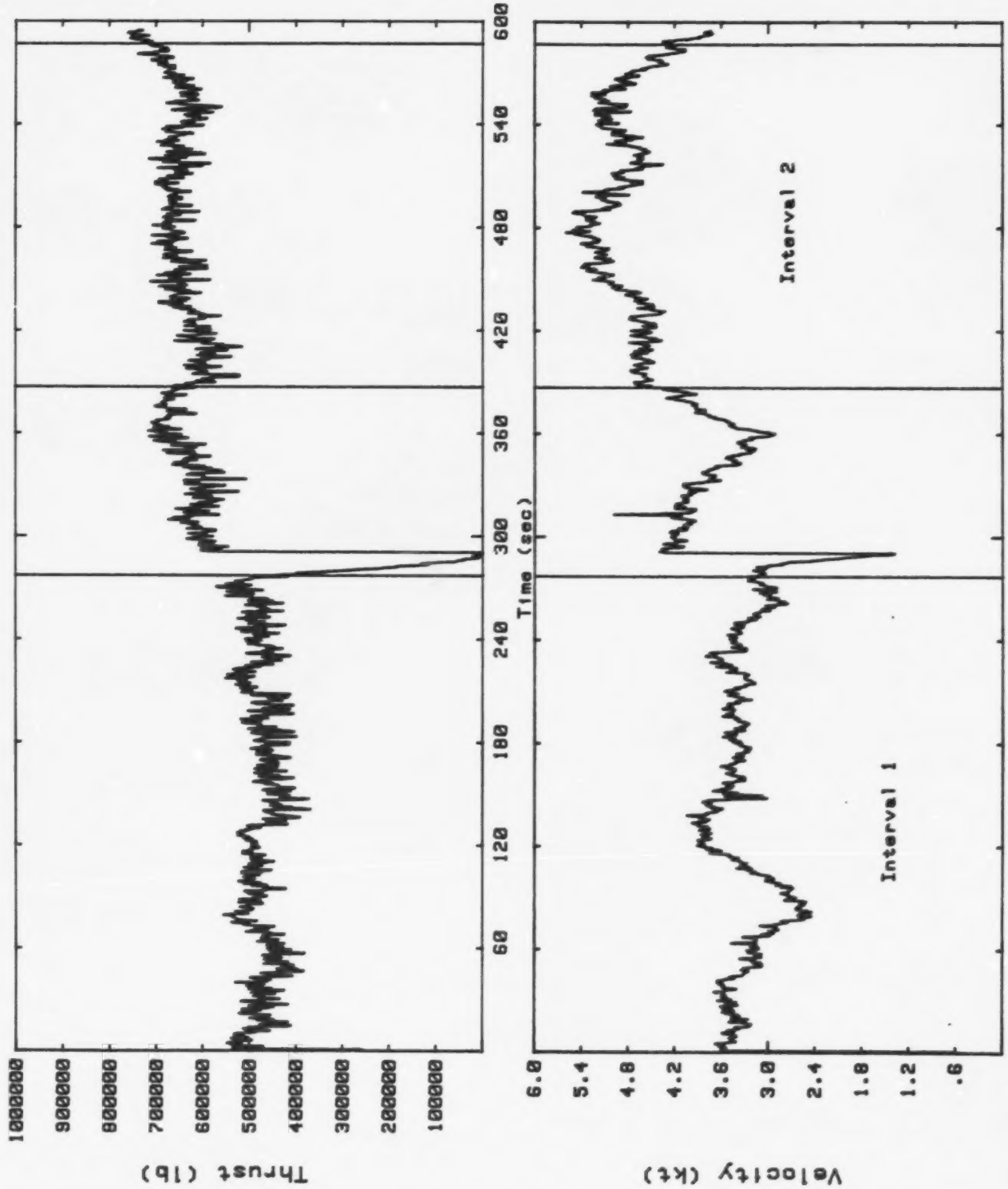


TEST NUMBER 002, January 10, 1984

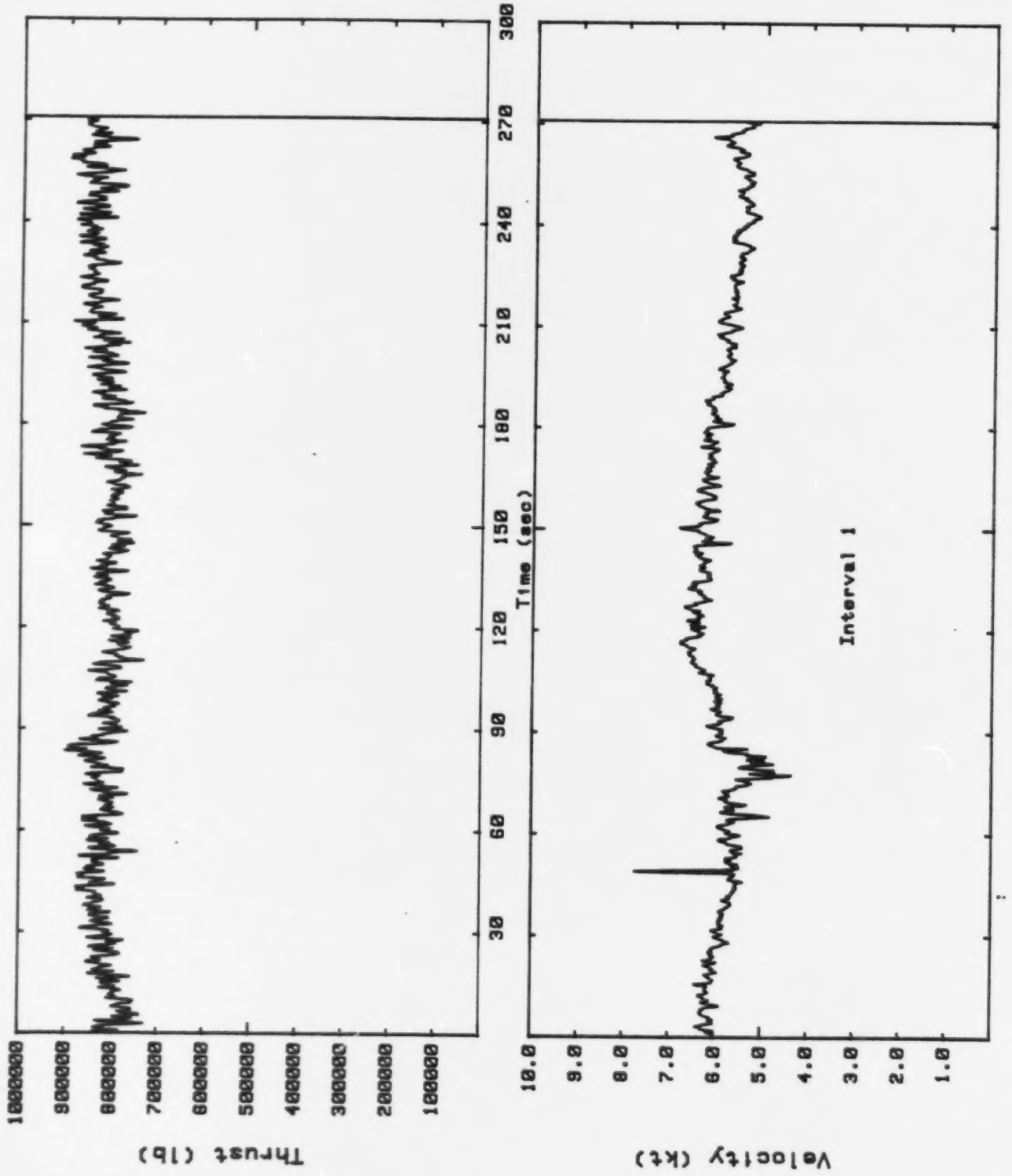


TEST NUMBER 003, January 10, 1984

TEST NUMBER 003, January 10, 1984

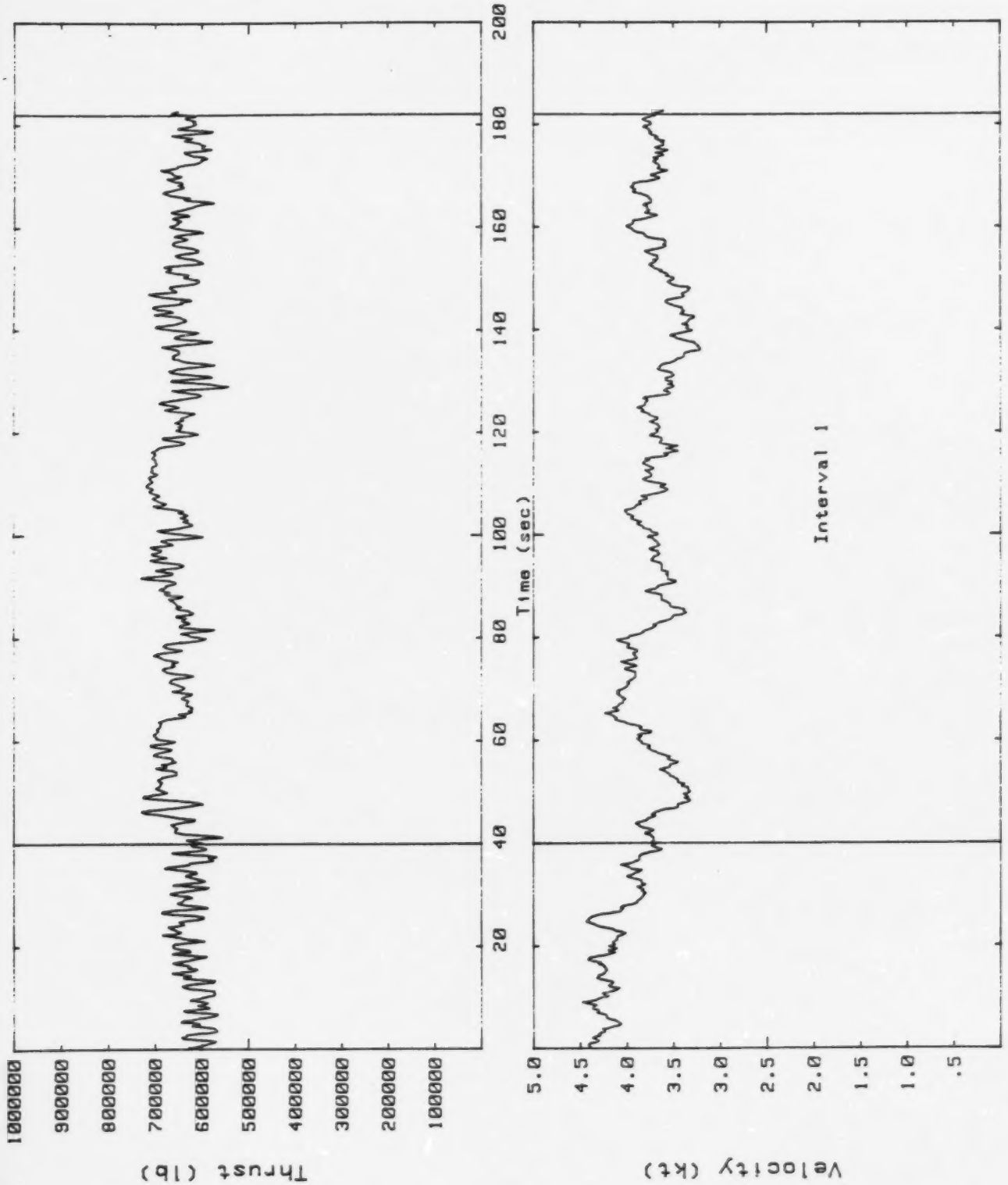


TEST NUMBER 004, January 10, 1984

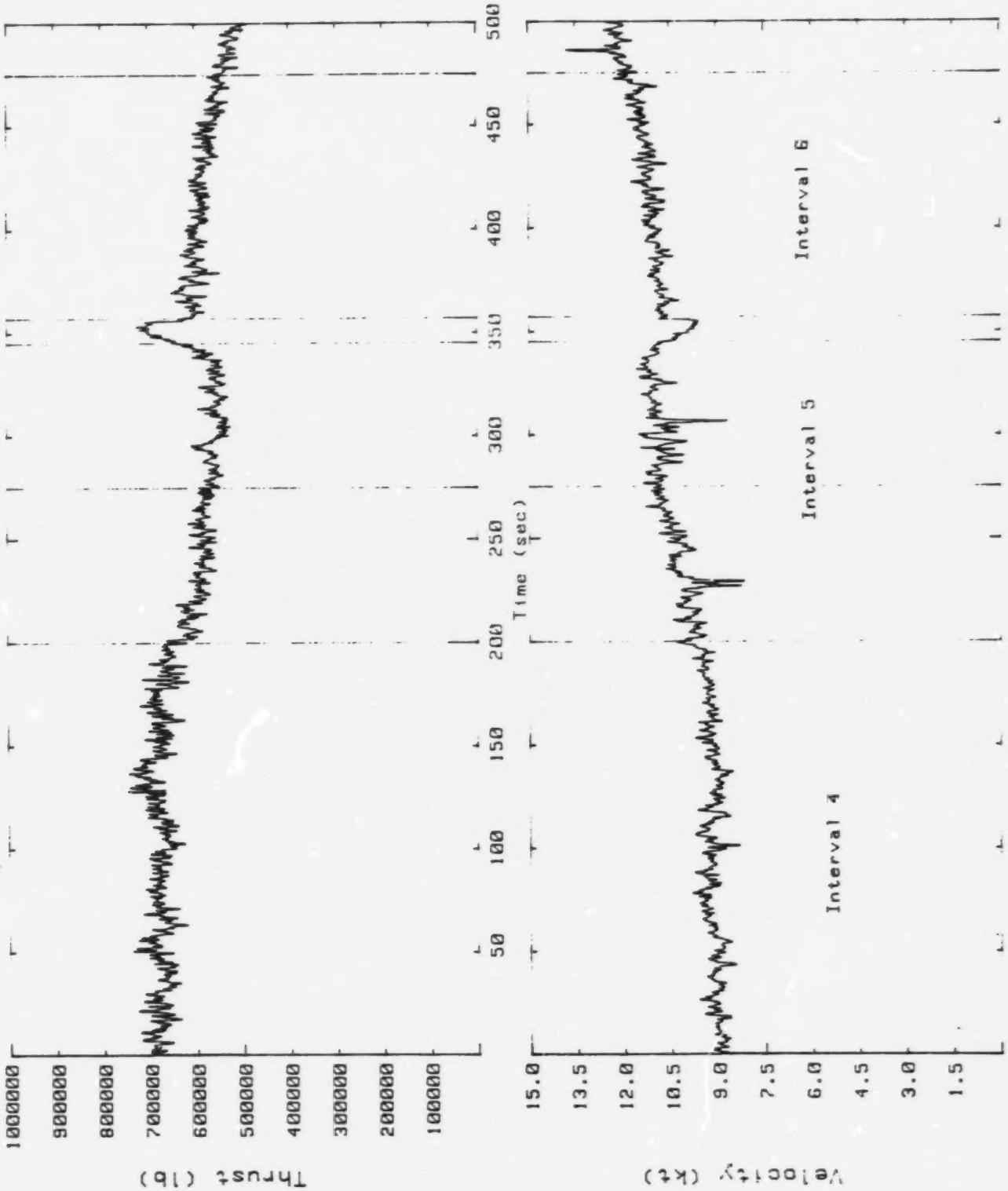


TEST NUMBER 005, January 11, 1984

TEST NUMBER 006, January 11, 1984

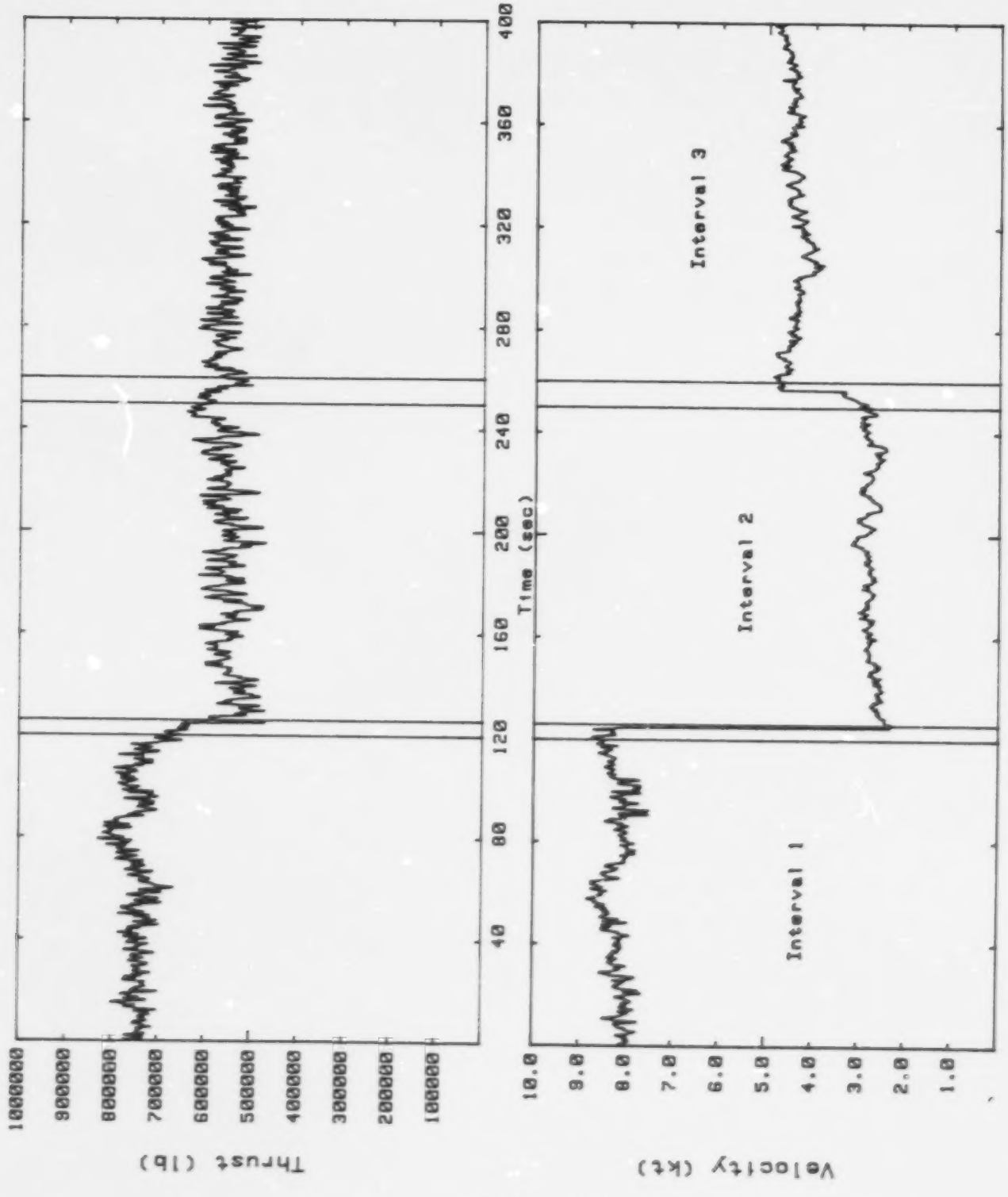


TEST NUMBER 008, January 12, 1984

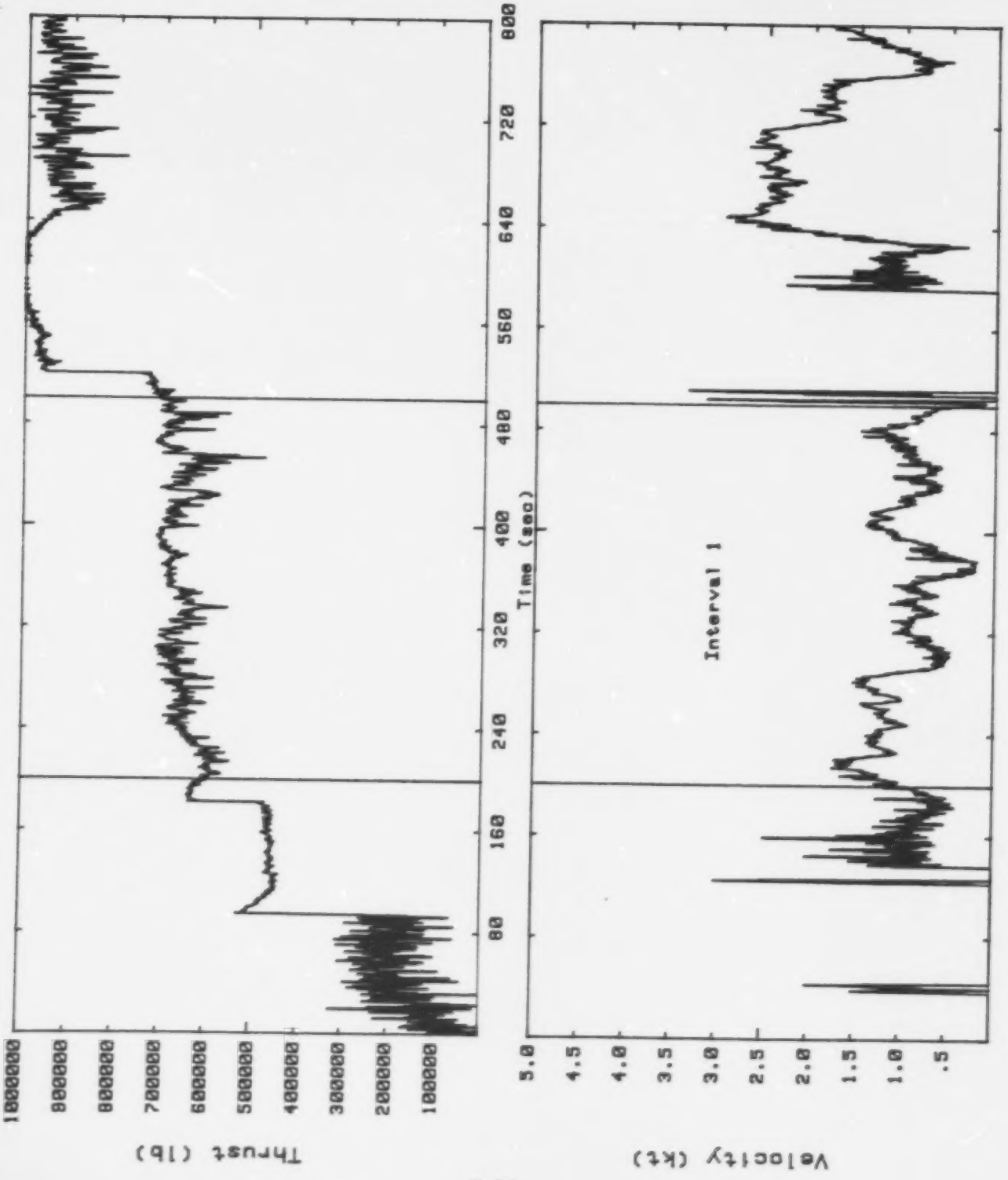


TEST NUMBER 007, January 12, 1984

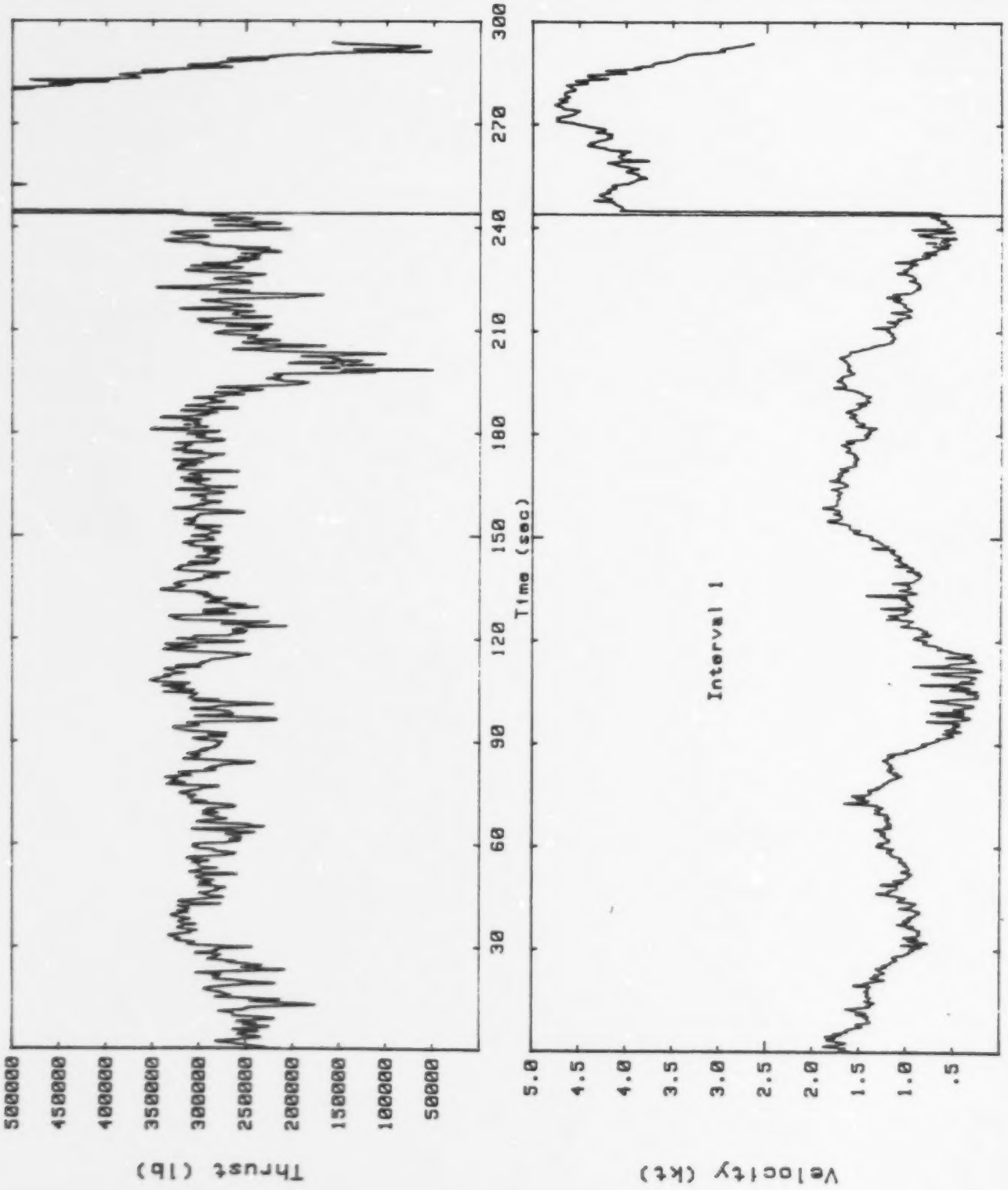
TEST NUMBER 008, January 12, 1984



TEST NUMBER 009, January 13, 1984

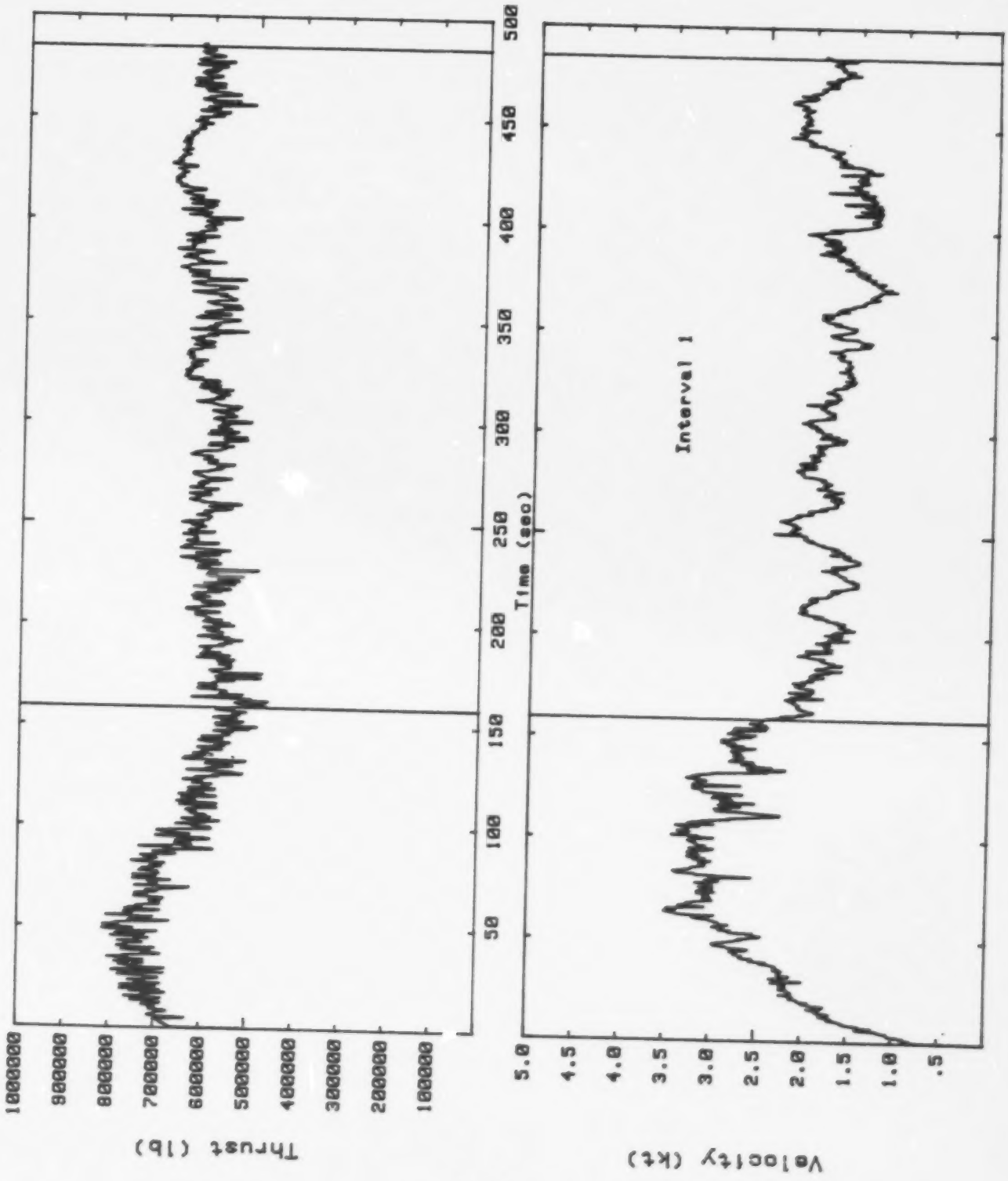


TEST NUMBER 010, January 13, 1984

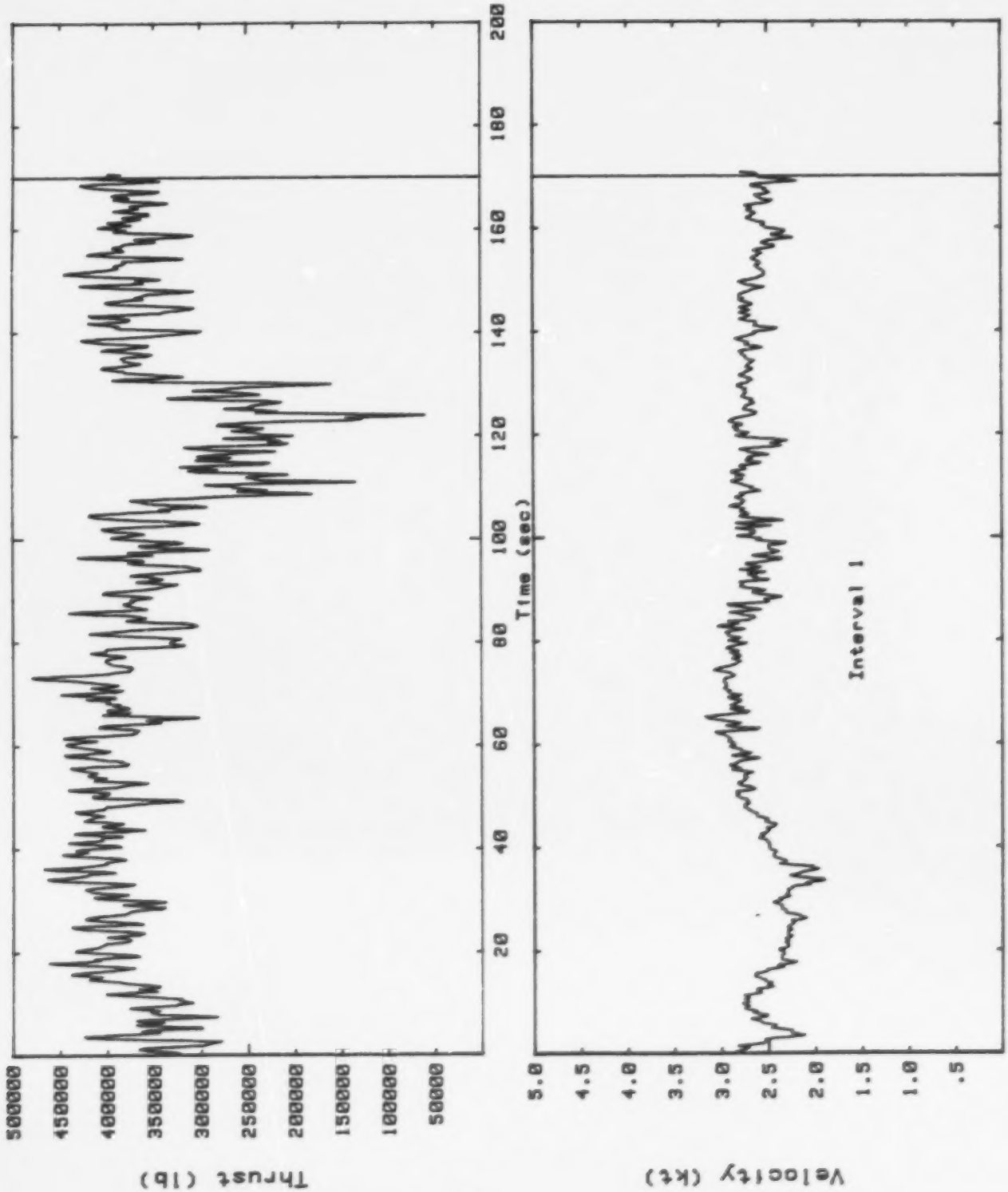


TEST NUMBER 011, January 13, 1984

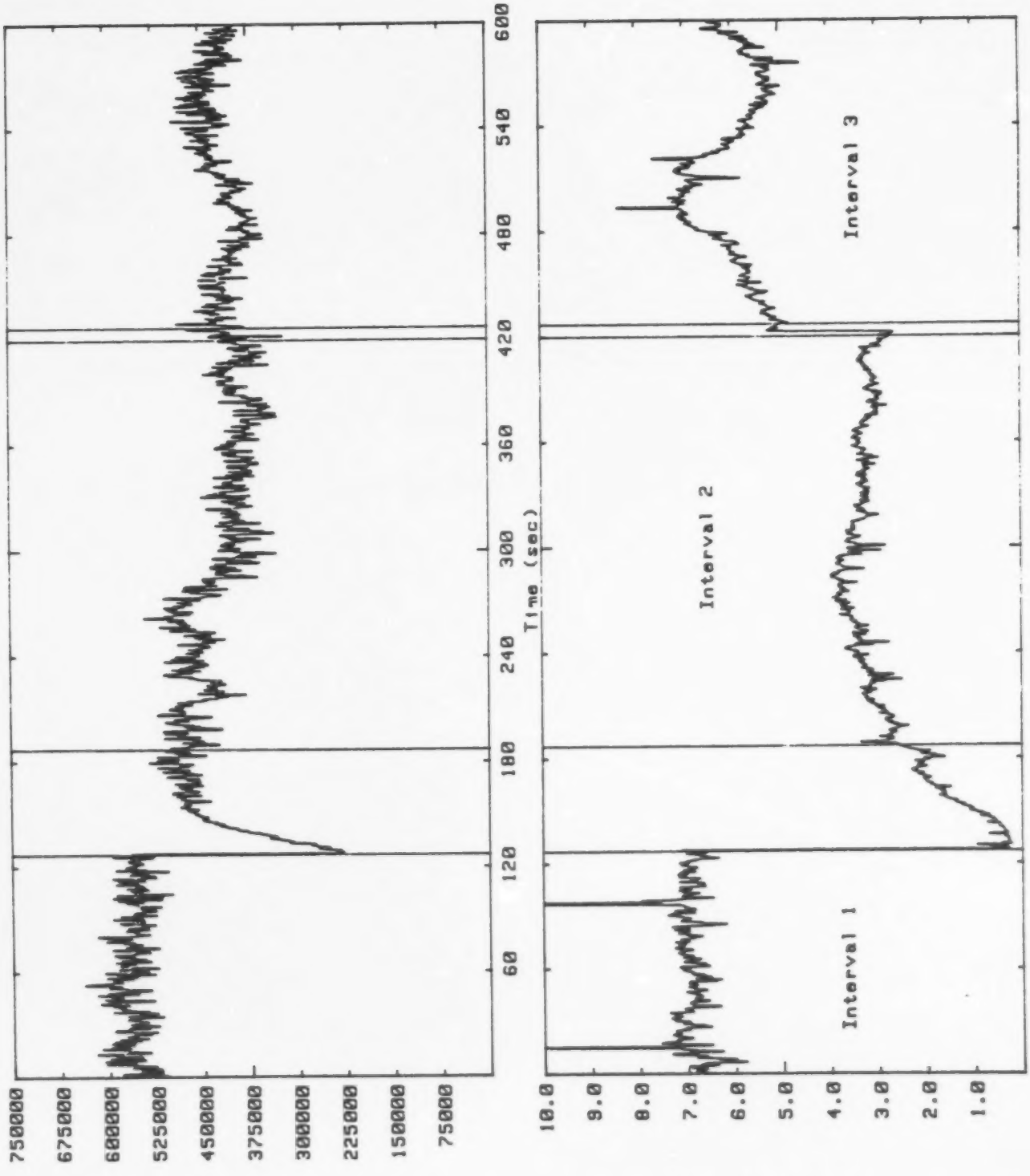
TEST NUMBER 011, January 13, 1984



TEST NUMBER 012, January 13, 1984



TEST NUMBER 013, January 13, 1984



APPENDIX C

METEOROLOGICAL CONDITIONS DURING THE TEST PERIOD FROM PILOT HOUSE LOGS

WIND SPEED
WIND DIRECTION
VISIBILITY
WEATHER
TEMPERATURE (DRY BULB)

NOTE: Throughout the test period, the weather was excellent. Data is given from the time the ship arrived at the ice edge (moored in the ice) until January 14, 1984.

MONDAY, JANUARY 9, 1984

HOURS	WIND DIRECTION TRUE	WIND FORCE (KNOTS)	VISIBILITY (MILES)	WEATHER (SYMBOLS)*	AIR TEMPERATURE(°F) DRY BULB
1000	120	15	10	BKN	23
1100	109	11	10	BKN	23
1200	109	11	10	BKN	23
1300	110	10	10	BKN	22
1400	110	10	10	BKN	22
1500	085	08	10	BKN	23
1600	085	08	10	BKN	25
1700	085	08	10	BKN	25
1800	085	11	10	BKN	23
1900	080	09	10	BKN	23
2000	090	10	10	OVC	24
2100	120	08	10	OVC	28
2200	120	09	10	OVC	30
2300	120	07	10	OVC	30
2400	130	09	8	OVC	32

* CLR - Clear or a Few Clouds
OVC - Overcast (More than 9 Tenths Clouds)
BKN - Broken Clouds (6 to 9 Tenths Clouds)
SCT - Scattered Clouds (1 to 5 Tenths Clouds)
S - Snow

TUESDAY, JANUARY 10, 1984

HOURS	WIND DIRECTION TRUE	WIND FORCE (KNOTS)	VISIBILITY (MILES)	WEATHER (SYMBOLS)*	AIR TEMPERATURE(°F) DRY BULB
0100	Calm	Calm	06	OVC, S	32
0200	Calm	Calm	07	OVC, S	29
0300	078	10	07	OVC, S	23
0400	120	12	08	OVC, S	22
0500	120	13	0.2	OVC, S	22
0600	080	16	0.5	OVC, S	22
0700	085	15	02	OVC, S	22
0800	085	15	1.5	OVC, S	20
0900	085	15	02	OVC, S	20
1000	110	14	10	OVC, S	19
1100	110	14	08	OVC, S	22
1200	081	09	08	BKN	20
1300	081	09	08	BKN	21
1400	092	15	08	BKN	22
1500	135	10	08	BKN	27
1600	145	10	07	BKN	25
1700	130	08	09	BKN	27
1800	103	08	09	BKN	26
1900	120	10	10	SCT	25
2000	132	10	10	SCT	25
2100	132	10	10	SCT	29
2200	140	12	10	SCT	29
2300	140	12	10	OVC	22
2400	190	12	10	OVC	22

* CLR - Clear or a Few Clouds
OVC - Overcast (More than 9 Tenths Clouds)
BKN - Broken Clouds (6 to 9 Tenths Clouds)
SCT - Scattered Clouds (1 to 5 Tenths Clouds)
S - Snow

WEDNESDAY, JANUARY 11, 1984

HOURS	WIND DIRECTION TRUE	WIND FORCE (KNOTS)	VISIBILITY (MILES)	WEATHER (SYMBOLS)*	AIR TEMPERATURE(°F) DRY BULB
0100	130	15	10	BKN	22
0200	130	15	10	BKN	22
0300	114	12	10	BKN	18
0400	117	13	10	BKN	22
0500	116	17	10	BKN	19
0600	108	15	10	BKN	15
0700	107	16	10	BKN	23
0800	107	16	06	OVC	24
0900	123	12	05	OVC, S	20
1000	123	12	05	OVC, S	23
1100	123	12	08	OVC, S	20
1200	115	15	09	OVC, S	17
1300	115	15	09	BKN	16
1400	090	17	09	BKN	17
1500	090	17	09	BKN	17
1600	090	17	10	OVC	17
1700	085	15	09	BKN	18
1800	080	17	10	BKN	17
1900	080	17	10	OVC	18
2000	330	12	10	OVC	18
2100	090	12	10	OVC	18
2200	080	15	10	OVC, S	17
2300	095	15	10	OVC, S	15
2400	095	15	10	OVC, S	15

* CLR - Clear or a Few Clouds
OVC - Overcast (More than 9 Tenths Clouds)
BKN - Broken Clouds (6 to 9 Tenths Clouds)
SCT - Scattered Clouds (1 to 5 Tenths Clouds)
S - Snow

THURSDAY, JANUARY 12, 1984

HOURS	WIND DIRECTION TRUE	WIND FORCE (KNOTS)	VISIBILITY (MILES)	WEATHER (SYMBOLS)*	AIR TEMPERATURE(°F) DRY BULB
0100	108	12	10	OVC, S	20
0200	108	12	08	OVC, S	19
0300	110	14	07	OVC, S	21
0400	110	14	06	OVC	26
0500	110	14	08	BKN	17
0600	120	13	08	OVC, S	16
0700	120	15	08	BKN	18
0800	125	15	10	BKN	18
0900	110	16	10	SCT	18
1000	120	16	10	SCT	20
1100	120	08	10	SCT	25
1200	185	07	10	SCT	34
1300	180	06	10	SCT	34
1400	170	03	10	SCT	36
1500	170	04	10	SCT	37
1600	160	02	10	SCT	35
1700	180	02	10	CLR	35
1800	140	09	10	SCT	35
1900	140	09	10	SCT	31
2000	140	07	10	SCT	33
2100	Calm	00	10	SCT	35
2200	Calm	00	10	SCT	33
2300	Calm	00	10	SCT	30
2400	Calm	00	10	SCT	29

* CLR - Clear or a Few Clouds
OVC - Overcast (More than 9 Tenths Clouds)
BKN - Broken Clouds (6 to 9 Tenths Clouds)
SCT - Scattered Clouds (1 to 5 Tenths Clouds)
S - Snow

FRIDAY, JANUARY 13, 1984

HOURS	WIND DIRECTION TRUE	WIND FORCE (KNOTS)	VISIBILITY (MILES)	WEATHER (SYMBOLS)*	AIR TEMPERATURE(°F) DRY BULB
0100	020	09	10	BKN	23
0200	010	07	10	BKN	23
0300	332	06	10	BKN	25
0400	332	06	10	SCT	23
0500	284	03	10	SCT	26
0600	010	03	10	SCT	25
0700	010	02	10	CLR	25
0800	Calm	Calm	10	CLR	32
0900	027	02	10	CLR	40
1000	Calm	Calm	10	SCT	40
1100	Calm	Calm	10	SCT	36
1200	Calm	Calm	10	SCT	36
1300	Calm	Calm	10	SCT	39
1400	330	05	10	SCT	41
1500	330	05	10	SCT	43
1600	330	04	10	SCT	38
1700	330	04	10	SCT	41
1800	000	06	10	SCT	39
1900	000	05	10	SCT	39
2000	Calm	Calm	10	SCT	40
2100	Calm	Calm	10	SCT	34
2200	073	04	10	SCT	39
2300	080	05	10	SCT	35
2400	035	03	10	SCT	33

* CLR - Clear or a Few Clouds
OVC - Overcast (More than 9 Tenths Clouds)
BKN - Broken Clouds (6 to 9 Tenths Clouds)
SCT - Scattered Clouds (1 to 5 Tenths Clouds)
S - Snow

SATURDAY, JANUARY 14, 1984

HOURS	WIND DIRECTION TRUE	WIND FORCE (KNOTS)	VISIBILITY (MILES)	WEATHER (SYMBOLS)*	AIR TEMPERATURE(°F) DRY BULB
0100	060	03	10	SCT	37
0200	085	03	10	SCT	36
0300	Calm	Calm	10	SCT	35
0400	068	06	10	SCT	35
0500	068	06	10	SCT	38
0600	062	03	10	SCT	35
0700	062	03	10	SCT	34
0800	Calm	Calm	10	SCT	37
0900	092	08	10	SCT	37
1000	092	08	10	SCT	30
1100	092	08	10	BKN	39
1200	098	09	10	BKN	42
1300	097	08	10	BKN	37
1400	096	06	10	BKN	36
1500	Calm	Calm	10	BKN	43
1600	020	05	10	BKN	35
1700	270	03	10	BKN	31
1800	130	03	10	BKN	32
1900	Calm	Calm	10	BKN	37
2000	Calm	Calm	10	SCT	33
2100	178	02	10	SCT	32
2200	Calm	Calm	10	SCT	29
2300	150	02	10	SCT	29
2400	150	02	10	SCT	33

* CLR - Clear or a Few Clouds
OVC - Overcast (More than 9 Tenths Clouds)
BKN - Broken Clouds (6 to 9 Tenths Clouds)
SCT - Scattered Clouds (1 to 5 Tenths Clouds)
S - Snow

APPENDIX D

COMPARISON OF ARCTEC ICE-THICKNESS METER (AIM) READINGS TO DATA FROM AUGERING AND A DESCRIPTION OF THE AIM

During the Antarctic level ice resistance tests, the ARCTEC Ice-Thickness Meter (AIM) was used in conjunction with augered ice thickness measurements. Initially, ice thickness readings were made using both methods to establish confidence with the AIM. Subsequently, the AIM was used to give ice thickness between augered holes to speed up the ice profiling operation. With a direct readout of ice thickness, the AIM can reduce augering manhours by 95%.

Figures D.1 and D.2 provide a comparison of ice thickness measurements between augered and AIM methods. It should be noted that differences between augered ice thickness and AIM thickness is just that. The bottom ice surface contour in some cases is smooth and in other cases was irregular. The irregular surface gave the appearance of bumps or surface indentations every several feet with an elevation change of three to four inches between extremes. The AIM gives an average reading over a twelve foot length whereas the augered thickness is for a specific point. Therefore, both sets of data are recorded without claiming either is the absolutely correct value. The point to be made is that the AIM appears to be an attractive tool for rapidly determining average ice thickness at any given location and that periodic measurements by ice augering should also be performed.

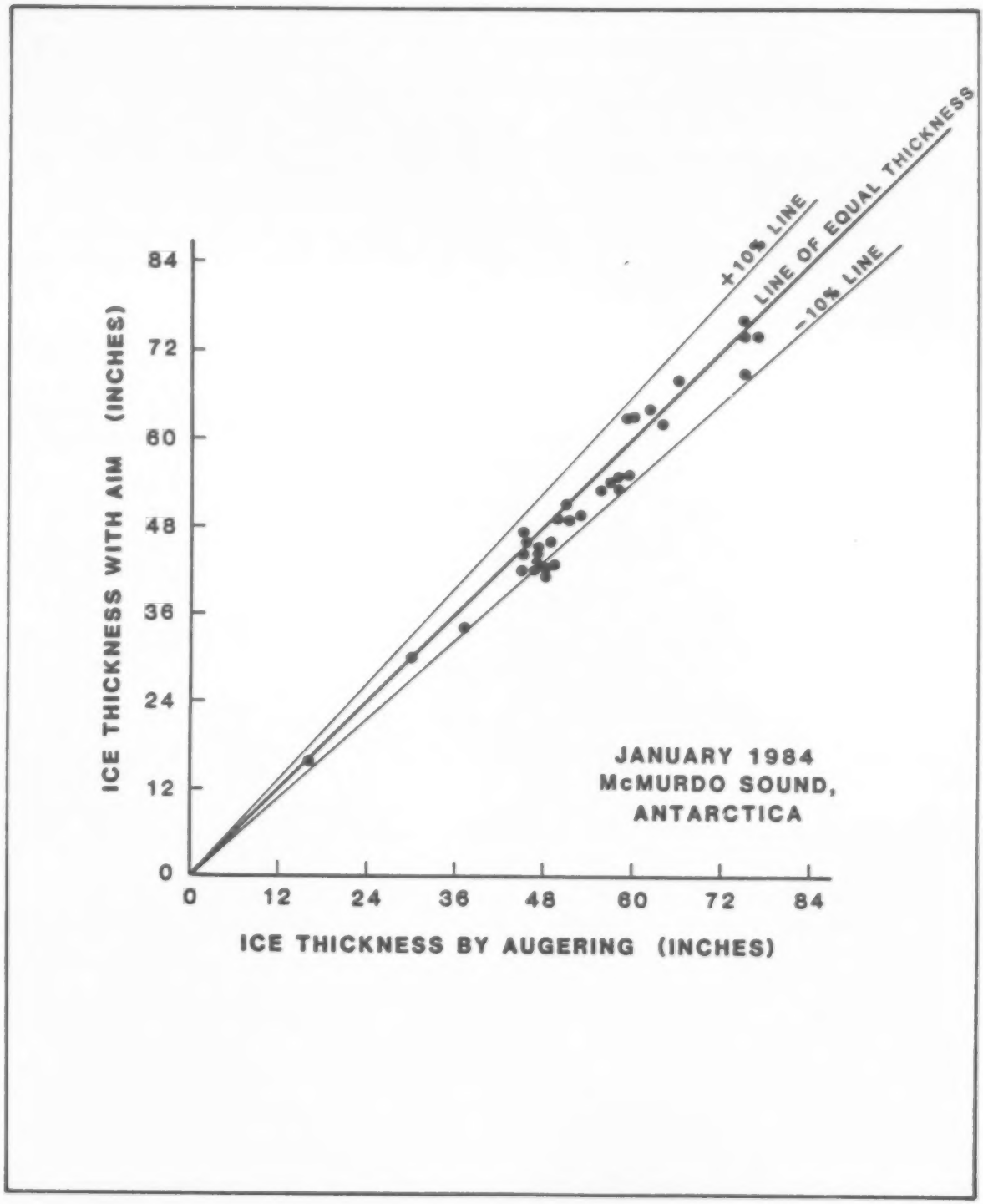


FIGURE D.1 COMPARISON OF ARCTEC ICE - THICKNESS METER TO ICE THICKNESS BY AUGERING (DATA IN TABLE D.1)

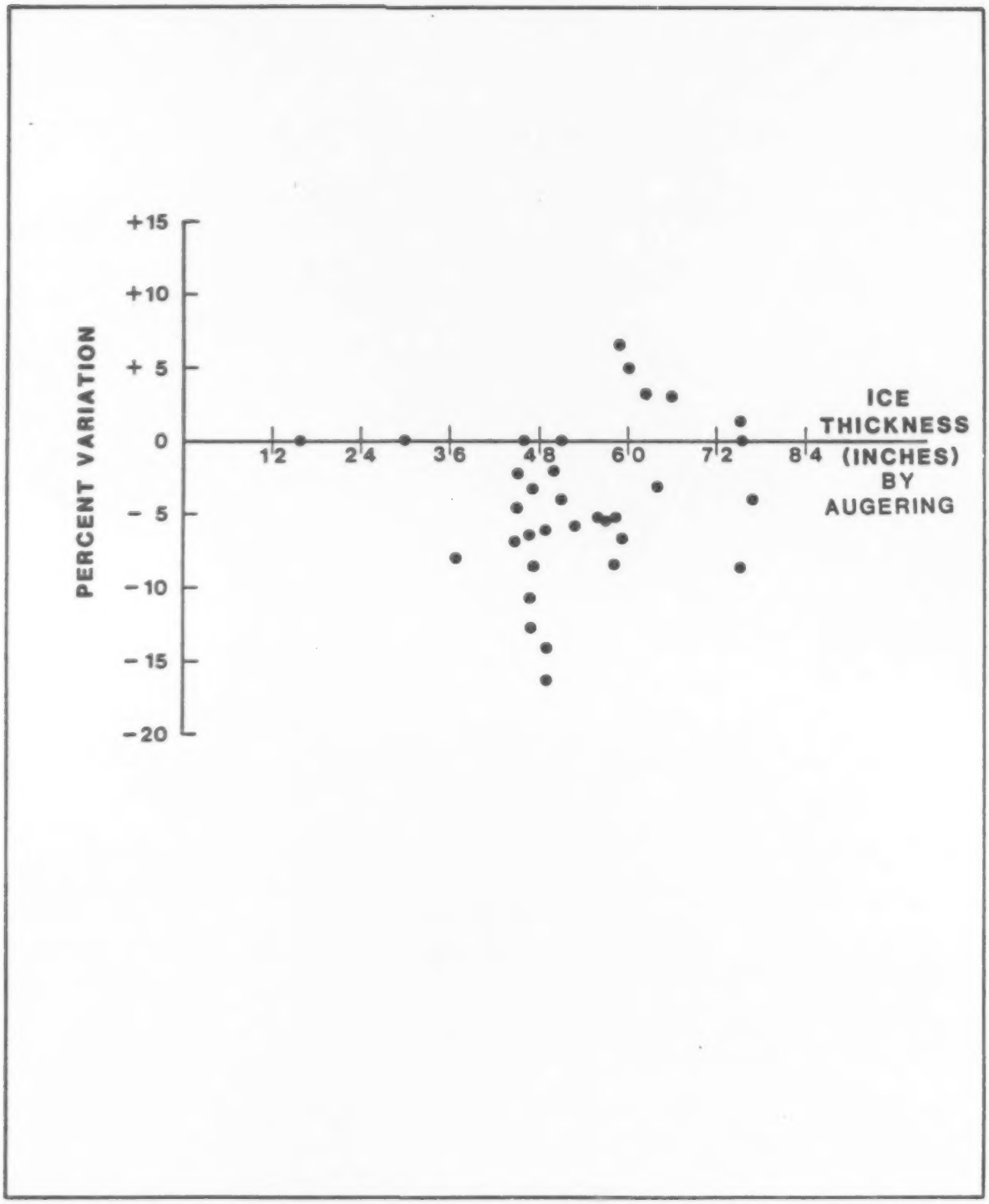


FIGURE D.2 PERCENT VARIATION IN ICE THICKNESS MEASUREMENTS BETWEEN AIM AND AUGERING (DATA IN TABLE D.1)

TABLE D.1

MEASUREMENT NUMBER	ICE THICKNESS BY AIM (inches)	ICE THICKNESS BY AUGERING (inches)
1	69.5	75
2	74	77
3	76	75
4	74.5	75
5	42	49
6	34	37
7	16	16
9	30	30
10	44	47
11	44	47
12	41	47
13	46	49
14	41	49
15	45.5	47
16	42	47
17	44	47
18	44	45
19	47	45
20	42	45
21	43	47
22	46	46
23	42	48
24	51	51
25	50	53
26	50	53
27	49	50
28	55	59
29	52.5	58
30	49	51
31	54	57
32	63	60
33	64	62
34	63	59
35	62	64
36	55	58
37	53	56
38	68	66

DESCRIPTION OF THE AIM

The AIM, as shown in Figure D.3, is a non-contacting, earth conductivity sensor that has been modified slightly to measure ice thickness. The basic principle of operation of the instrument is illustrated in Figure D.4. A transmitter coil located at one end of the instrument induces eddy currents in the earth. Under the conditions of frequency and coil separation as maintained by the AIM, the magnitude of any one of the eddy current loops is proportional to the conductivity of the earth in the vicinity. Each of these current loops generates a secondary magnetic field that is proportional to the current flowing in the loop. A receiver coil intercepts these secondary magnetic fields and produces a signal that is linearly related to the terrain conductivity.

Over sea ice, as shown in Figure D.5, the eddy current flow in sea ice is negligible compared to the eddy currents set up in seawater. This layering is similar to a highly resistive overburden with a conductive ore body below. The magnitude and phase angle of the secondary field compared to the transmitted field is used to estimate the distance to the seawater (i.e., the ice thickness) and, as a by-product of the analysis, the conductivity of the seawater.

The AIM specifications are briefly described in Table D.2. The operator carries the AIM while walking planned transverses over the ice floe. The responses are measured on the instrument panel, shown in Figure D.6 and recorded by an assistant. The numbers are then transferred to a nomograph from which the ice thickness and water conductivity values are obtained. During spring 1984, a direct readout meter will be available which will eliminate the need to manually record voltages from the instrument panel.

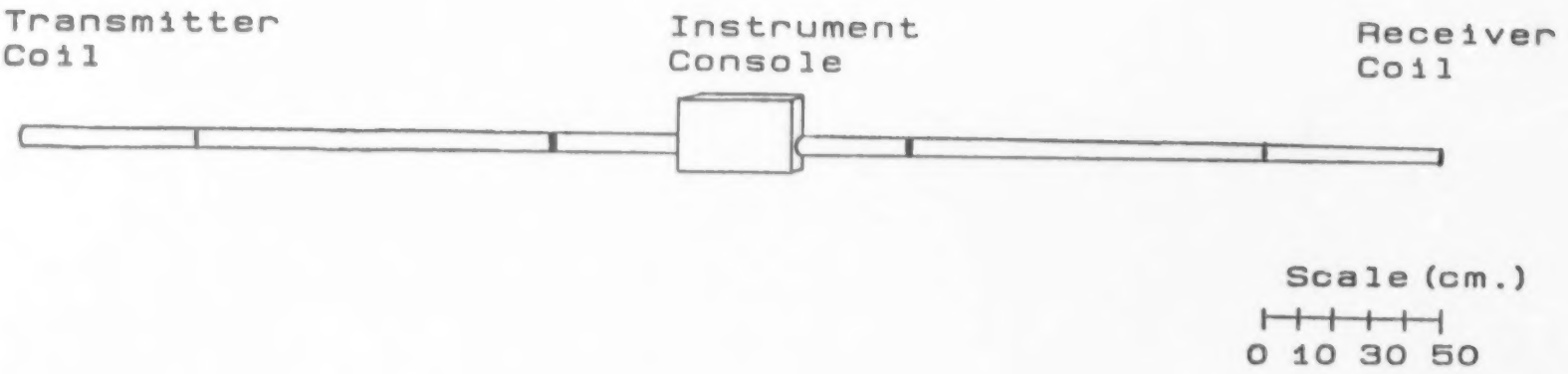
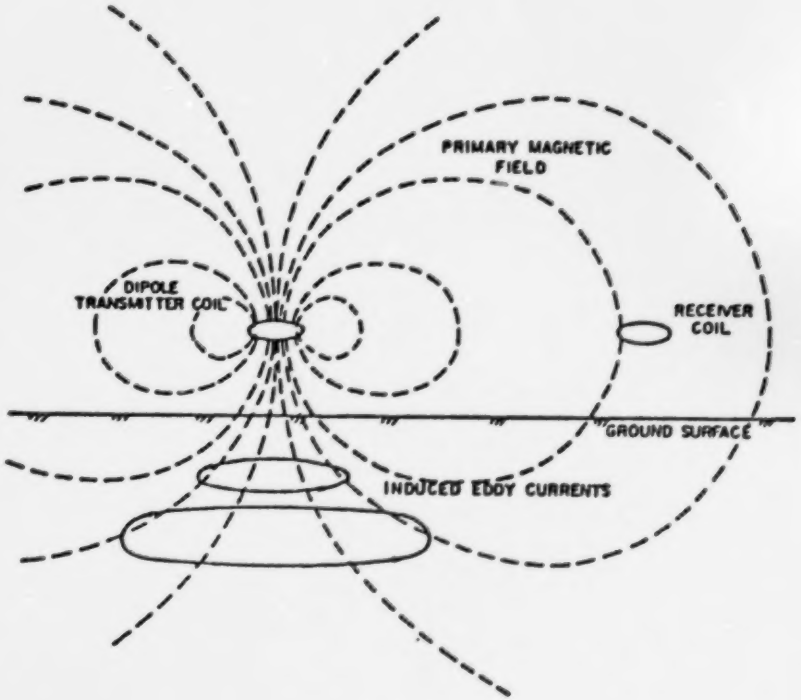
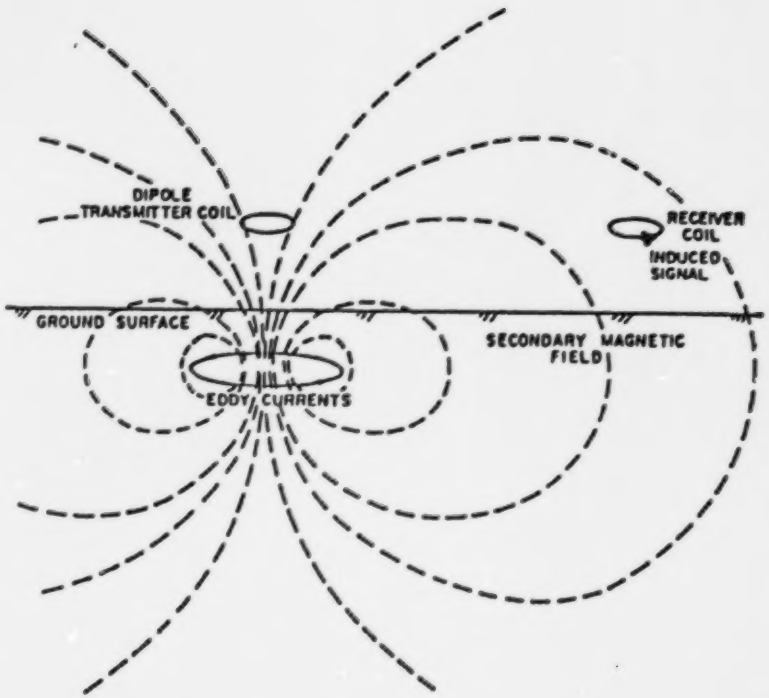


FIGURE D.3 AIM ICE THICKNESS METER



PRIMARY FIELD



SECONDARY FIELD

FIGURE D.4 BASIC OPERATING PRINCIPLES OF MAGNETIC INDUCTION

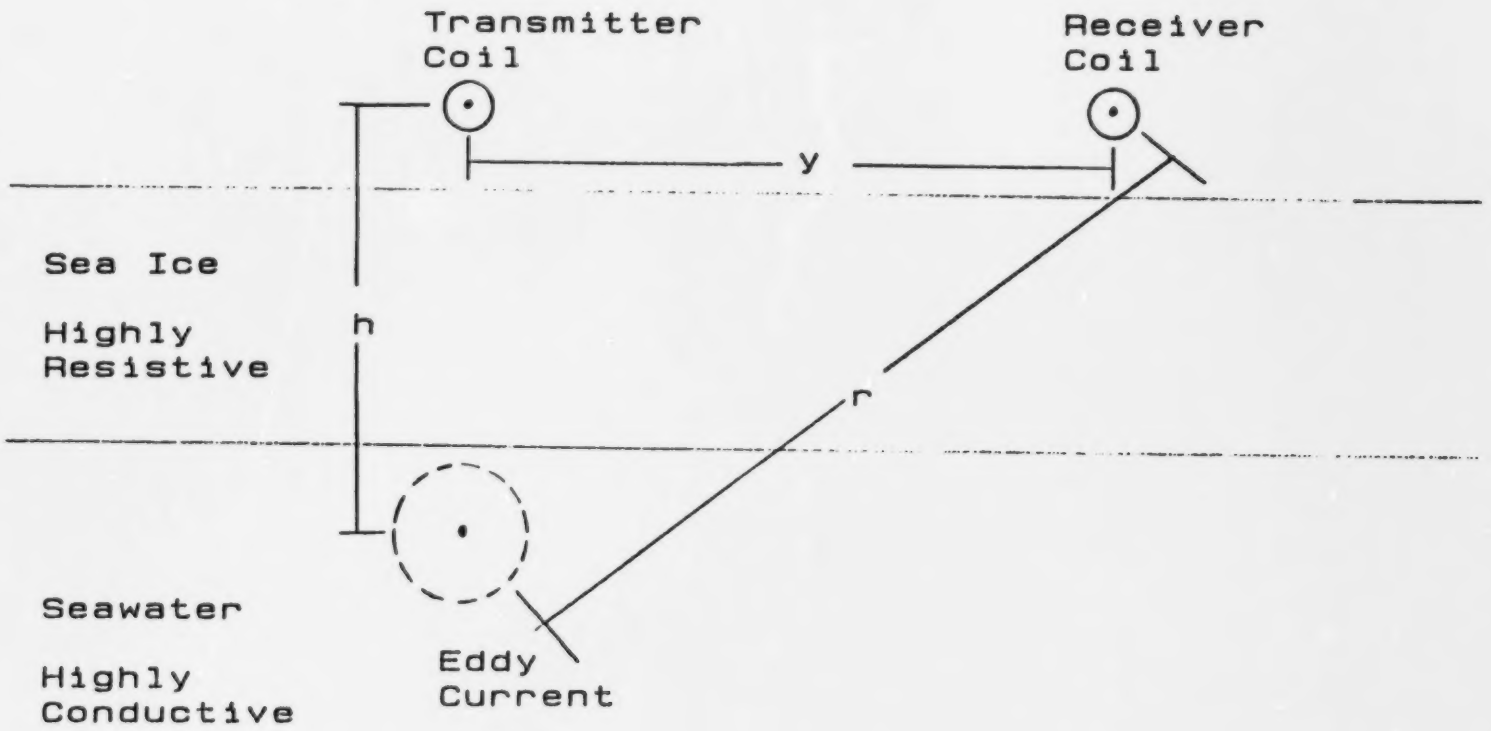


FIGURE D.5 AIM OPERATED OVER SEA ICE

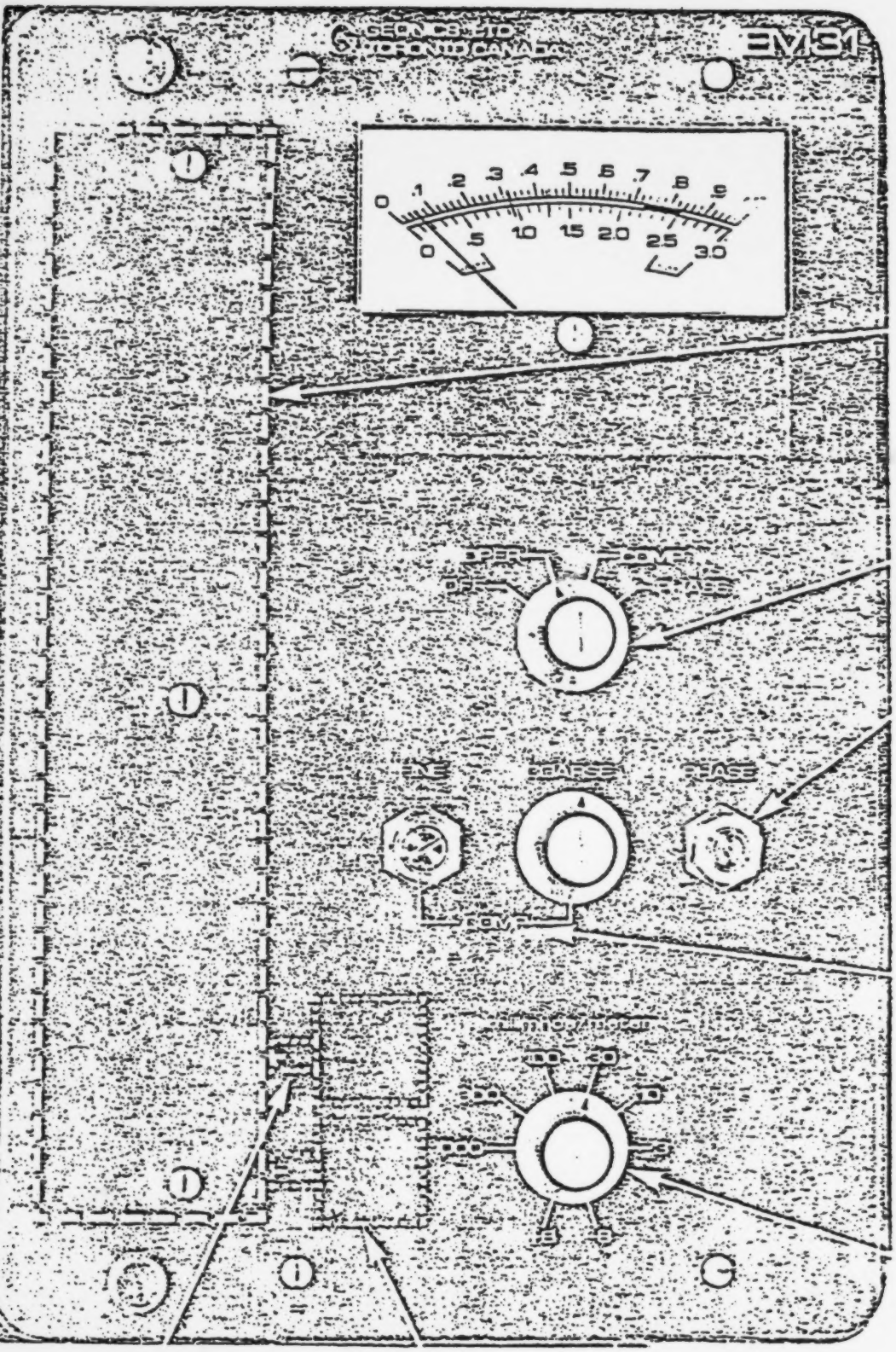


FIGURE D.6 AIM INSTRUMENT CONTROLS

TABLE D.2 AIM SPECIFICATIONS

MEASURED QUANTITY	Apparent conductivity of the ground in millimhos per meter
PRIMARY FIELD SOURCE	Self-contained dipole transmitter
SENSOR	Self-contained dipole receiver
INTERCOIL SPACING	3.66 meters
OPERATING FREQUENCY	9.8 kHz
POWER SUPPLY	8 disposable alkaline 'C' cells (approx. 20 hrs life continuous use)
CONDUCTIVITY RANGES	3, 10, 30, 100, 300, 1000 mmhos/meter
MEASUREMENT PRECISION	±2% of full scale
MEASUREMENT ACCURACY	±5% at 20 millimhos per meter
NOISE LEVEL	<0.1 millimhos per meter
OPERATOR CONTROLS	∘ Mode Switch ∘ Conductivity Range Switch ∘ Phasing Potentiometer ∘ Coarse Inphase Compensation ∘ Fine Inphase Compensation
DIMENSIONS	Boom : 4.0 meters extended 1.4 meters stored Console : 24 x 20 x 18 cm Shipping Crate : 155 x 42 x 28 cm
WEIGHT	Instrument Weight: 9 kgm Shipping Weight: 23 kgm

APPENDIX E

COMPARATIVE ANALYSIS OF ANTARCTIC LEVEL ICE RESISTANCE DATA OF THE USCGC POLAR SEA (RICE MODEL)

INTRODUCTION

Icebreaking resistance tests were performed using the USCGC POLAR SEA during its Antarctic deployment in January 1984. The results of these tests are reported in the main body of this report. A total of thirty test runs were conducted in ice ranging in thickness from 3.08 to 5.71 feet (0.94 to 1.74 m) at varying speeds from as low as 0.9 knots to 11.2 knots. The ice resistance was measured and averaged for each test.

The ice was generally weak and the reported flexural strength values were mostly 45 psi (310 kPa) except for the first ten runs when the ice strength was only 37.4 psi (258 kPa).

The ice resistance was calculated from measured thrust, and accounted for thrust deduction and open water resistance. Therefore, the reported values were net ice resistance values which exclude open water resistance.

The objective of this Appendix is to provide a comparison between the measured full scale ice resistance data and the semi-empirical ice resistance prediction model "RICE". The latter was the result of a major effort made during 1981-82 which was jointly supported by Transport Canada and the U.S. Maritime Administration and reported by J.W. Lewis, V. Bulat, I. Glen, and T. Kotras [4]. The results of this comparative evaluation are reported in the following sections.

RICE PREDICTIONS AND ANALYSIS

The RICE model was used to predict the resistance of the POLAR SEA under the reported test conditions of ice thickness, strength, and ship speed. The friction factor was 0.2. The input data for the POLAR SEA are listed in Table E.1.

A complete listing of the RICE results is given in Table E.2.

A comparison of predicted versus measured resistance values is shown in Figure E.1. The predictions are consistently lower than the measurements with a mean predicted resistance of 305,907.6 lbs compared to a mean measurement of 479,120.2 lbs. The correlation coefficient between the measured and predicted values is 0.7867 thus signifying a high scatter in the results. A linear regression would produce a relationship of the form:

$$R(\text{predicted}) = 0.66125\ R(\text{measured}) - 10{,}913 \text{ lbs}$$

The linear relationship is plotted on Figure E.1.

Assuming that the measured resistance is correct, the prediction error was calculated as follows:

$$\text{Error}(\%) = \frac{R_{pred} - R_{meas}}{R_{meas}} \times 100$$

This parameter was examined to determine how it is influenced by the major variables. Figures E.2 through E.5 illustrate the variation of the error(%) with:

- ice thickness, ft.
- ship speed, kts.
- measured resistance
- flexural strength.

The only trend which could be detected was that of speed dependence which may be represented in a linear form as given by:

$$\text{Error}(\%) = 3.5827\ V - 50.6475$$

It is shown that the error increases at lower speeds and converges to zero at higher speeds. No conclusion trend was observed for dependence of Error(%) on ice thickness or the measured resistance. It should be noted that for the mean speed of 4.0 kts, the Error(%) is -36.33% which explains most of the under-predicted resistance values.

The cross correlation matrix between the Error(%) and significant variables is given below:

	H	V	R_{meas}	R_{pred}	σ_f	Err(%)
H	1	-0.410	0.494	0.149	0.025	-0.297
V		1	0.464	0.824	0.331	0.716
R_{meas}			1	0.787	0.269	0.044
R_{pred}				1	0.433	0.637
σ_f					1	0.418
Err(%)						1

The high correlation between V and Error(%) is probably due to high cross correlation of V with R_{pred}.

The difference between predicted and measured resistance values are relatively large, and only about one quarter of the data is within ±25% prediction bounds.

Further verification of the field measurements and ice conditions and comparative evaluation of the breaking patterns as observed and as generated in the RICE model will be necessary to determine whether (and what) changes have to be made to the program.

For instance, the ice flexural strength was calculated based on measurements of temperature and salinity. At the same time, the ice was observed to have melt pools on its top. This is likely to influence the fracture characteristics of the ice including flexural strength and energy required to break the ice in flexure because of the increased viscous behaviour of the ice. Another observation was that related to piece size (or cusp size in the model) while icebreaking. The Antarctic ice produced generally larger piece sizes. The RICE model accounts for piece size in accordance with available empirical data on several ships (not including the Polar Class), and the cusp proportions are based on empirical observations. Should significantly different data be true for the Antarctic tests, the adjustments of RICE could be made accordingly. This change would probably require a review of all seven empirical coefficients embedded in the mathematical model.

FIGURE E.1

1341C POLAR SEA ANTARCTIC DEPLOYMENT

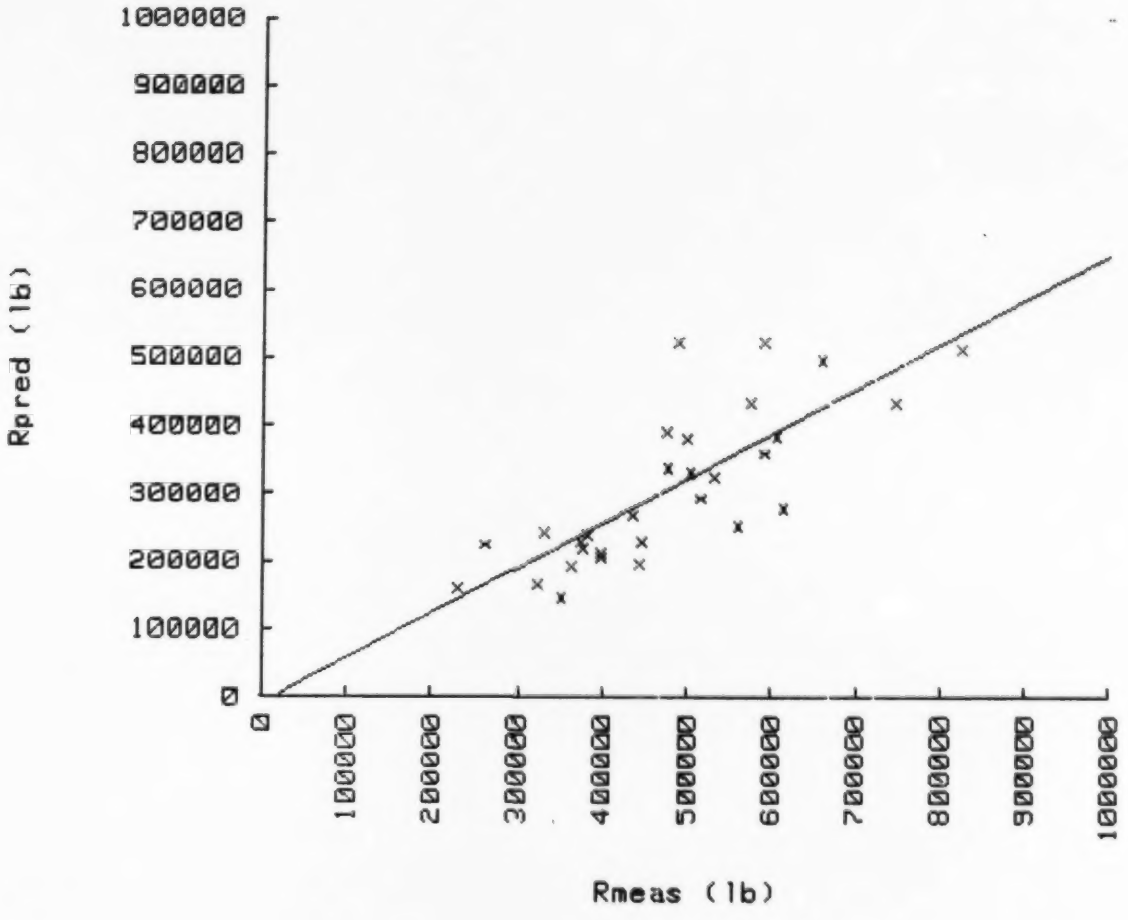


FIGURE E.2

1341C POLAR SEA ANTARCTIC DEPLOYMENT

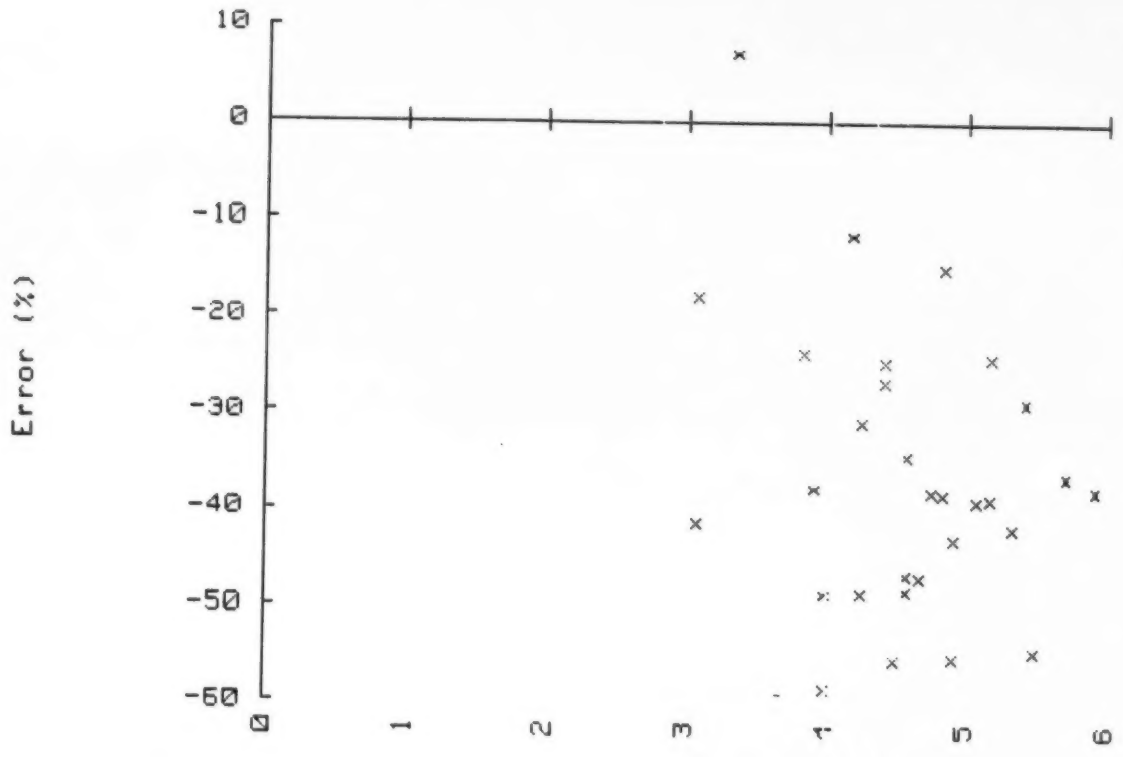


FIGURE E.3

1341C POLAR SEA ANTARCTIC DEPLOYMENT

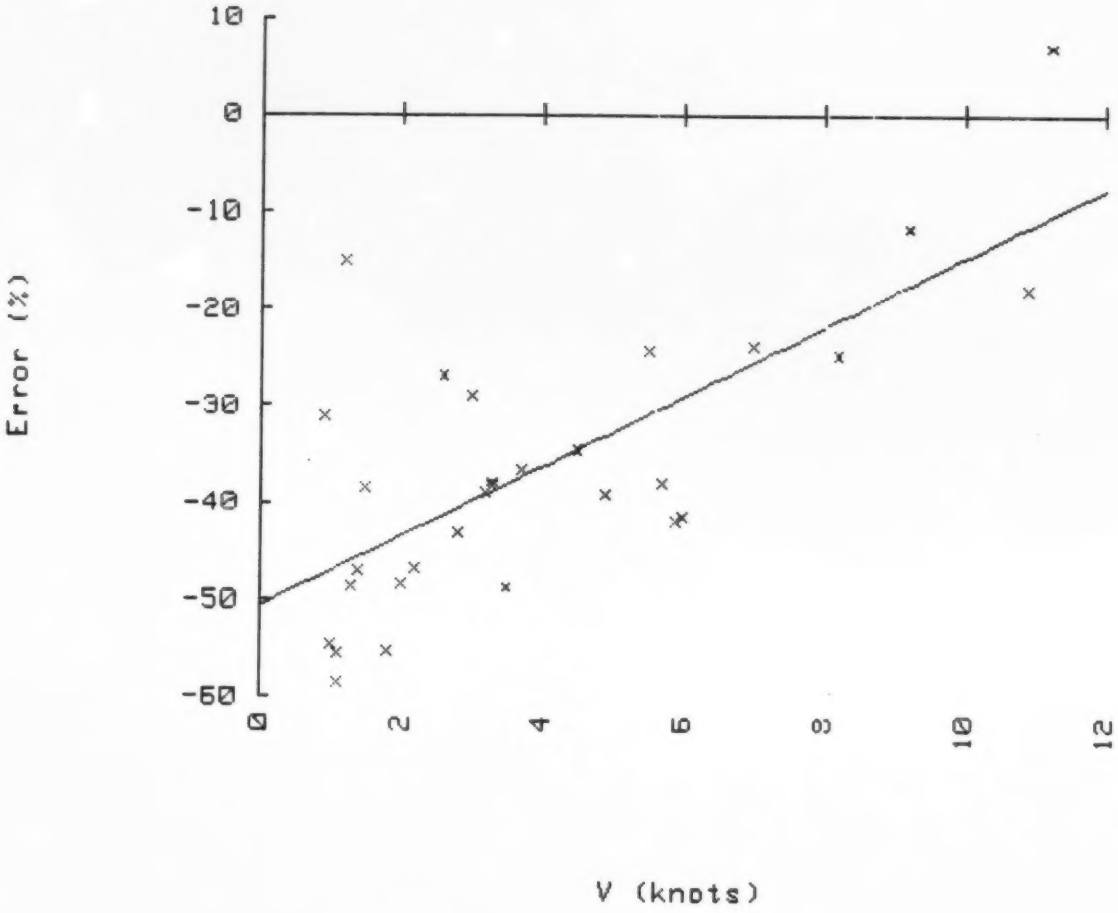


FIGURE E.4

1341C POLAR SEA ANTARCTIC DEPLOYMENT

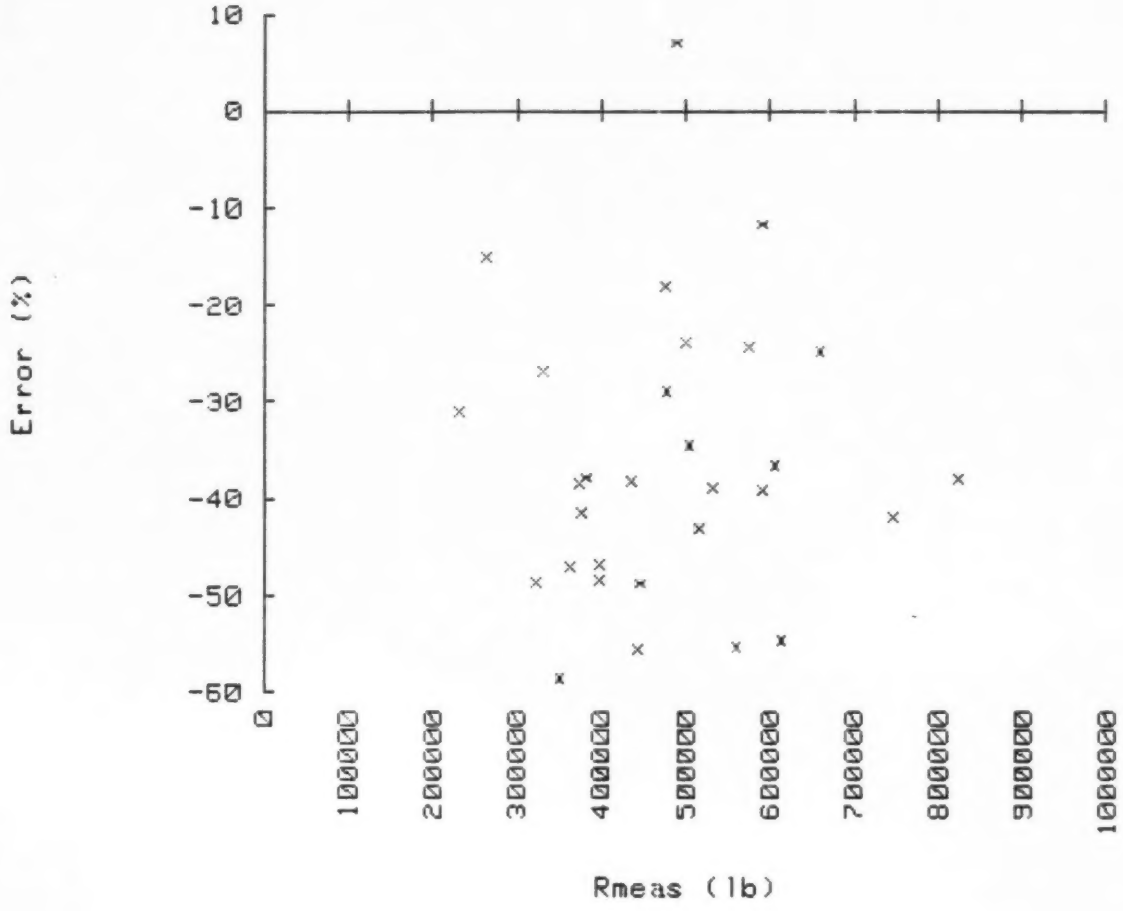


FIGURE E.5

1341C POLAR SEA ANTARCTIC DEPLOYMENT

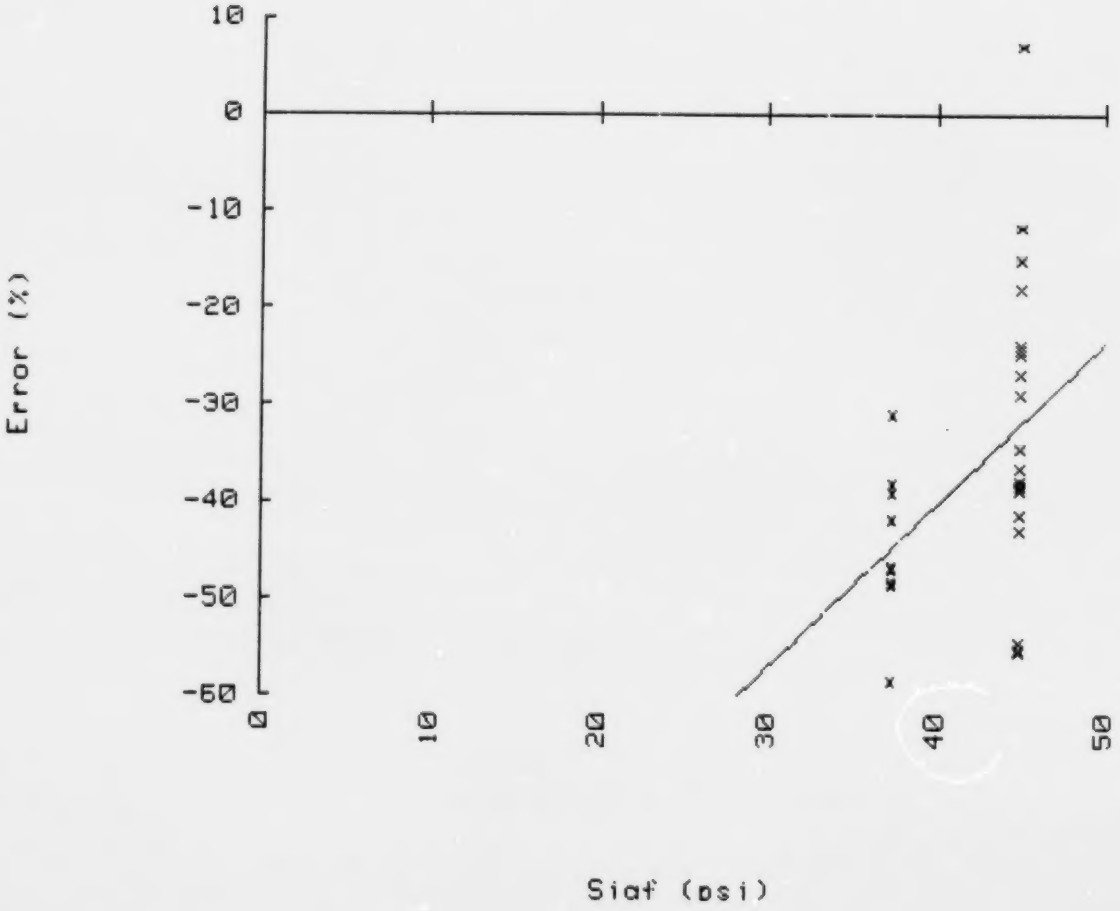


TABLE E.1

SHIP: POLAR SEA (Antarctic Deployment)

# of offsets: 21

1 = 0	2 = 2.553	3 = 5.232	4 = 7.455
5 = 9.182	6 = 10.465	7 = 11.265	8 = 11.684
9 = 11.798	10 = 11.798	11 = 11.684	12 = 11.494
13 = 11.252	14 = 10.922	15 = 10.389	16 = 9.652
17 = 8.636	18 = 6.604	19 = 5.22	20 = 2.705
21 = 0			

# of angles: 9

	ALFA	BETA
1	28	60
2	27	56
3	24	49
4	20.25	44.5
5	14.75	37.2
6	10	26.2
7	6.5	18
8	3.25	15.8
9	0	15

PARTICULARS- LBP= 107.2896 BEAM= 23.5966 DRAFT= 8.3058

COEFFICIENTS- BLOCK= .582 WATERPLANE= .733 MIDSHIPS= .852

PROPS= 3

CENTER SHAFT- POWER(kW)= 1549 DIAM= 4.877 RPS= 1.75

WING SHAFTS- POWER(kW)= 1549 DIAM= 4.877 RPS= 1.75

ADV. INCREMENT= .2 TIME INCREMENT= .1

FRICTION FACTOR= .2 R-K STEPS= 3

CASES:

V ship	H ice	SIG f
.56584	1.2192	257.873
1.8004	1.2192	257.873
.46296	1.2954	257.873
.66872	1.2954	257.873
1.0288	1.395984	257.873
1.13168	1.395984	257.873
.72016	1.423416	257.873
1.69752	1.4478	257.873
2.52056	1.548384	257.873
3.03496	1.624584	257.873
.7716	1.472184	310.275
1.5432	1.652016	310.275
1.64608	1.575816	310.275
1.90328	1.740408	310.275
2.93208	1.804416	310.275
4.21808	1.347216	310.275
1.44032	1.499616	310.275
2.3148	1.395984	310.275
4.73248	1.271016	310.275
5.60696	.938784	310.275
5.76128	1.014984	310.275
.5144	1.6764	310.275
.61728	1.472184	310.275
2.8292	1.575816	310.275
.56584	1.3716	310.275
.92592	1.499616	310.275
1.33744	1.347216	310.275
3.6008	1.167384	310.275
1.69752	1.194816	310.275
3.0864	.938784	310.275

TABLE E.2 LISTING OF RICE RESISTANCE PREDICTIONS

DATE: 4 : 6
TIME: 14 : 50 : 13

SHIP: POLAR SEA (Antarctic Deployment)

# of offsets: 21

1 = 0	2 = 2.553	3 = 5.232	4 = 7.455
5 = 9.182	6 = 10.465	7 = 11.265	8 = 11.684
9 = 11.798	10 = 11.798	11 = 11.684	12 = 11.494
13 = 11.252	14 = 10.922	15 = 10.389	16 = 9.652
17 = 8.636	18 = 6.604	19 = 5.22	20 = 2.705
21 = 0			

# of angles: 9

	ALFA	BETA
1	28	60
2	27	56
3	24	49
4	20.25	44.5
5	14.75	37.2
6	10	26.2
7	6.5	18
8	3.25	15.8
9	0	15

PARTICULARS(meters)-LBP= 107.2896 BEAM= 23.5966 DRAFT= 8.3058
COEFFICIENTS- BLOCK= .582 WATERPLANE= .733 MIDSHIPS= .852

# of PROPS: 3
CENTER SHAFT- POWER(kW)= 1549 DIAM(meters)= 4.877 RPS= 1.75
WING SHAFT- POWER(kW)= 1549 DIAM(meters)= 4.877 RPS= 1.75

ADV. INCREMENT= .2 TIME INCREMENT= .1
FRICTION FACTOR= .2 R-K STEPS= 3

****

1) ICE THICKNESS= 1.2192 meters
ELASTIC MODULUS= 1547.238 MPa
FLEXURAL STRENGTH= 257.873 KPa
CRUSHING STRENGTH= 773.619 KPa

VELOCITY= .56584 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIST	BREAKING FRICTION
-645,876	-1,905	-219,731	-132,260

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-90,498	-50,115	-84,007	-69,264

****

TABLE E.2 (con't.)

2) ICE THICKNESS= [illegible]
meters
ELASTIC MODULUS= 1547.238
MPa
FLEXURAL STRENGTH= 257.873
KPa
CRUSHING STRENGTH= 773.619
KPa

VELOCITY= 1.8004 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,017,127	-17,332	-219,731	-162,326

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-234,826	-246,973	-84,007	-69,264

****

3) ICE THICKNESS= 1.2954
meters
ELASTIC MODULUS= 1547.238
MPa
FLEXURAL STRENGTH= 257.873
KPa
CRUSHING STRENGTH= 773.619
KPa

VELOCITY= .46296 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-711,035	-1,301	-248,838	-151,985

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-87,738	-58,407	-90,543	-73,523

****

4) ICE THICKNESS= 1.2954
meters
ELASTIC MODULUS= 1547.238
MPa
FLEXURAL STRENGTH= 257.873
KPa
CRUSHING STRENGTH= 773.619
KPa

VELOCITY= .66872 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-736,693	-2,617	-248,838	-154,156

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-107,116	-62,516	-90,543	-73,523

TABLE E.2 (con't.)

5) ICE THICKNESS= 1.395984
meters
ELASTIC MODULUS= 1547.238
MPa
FLEXURAL STRENGTH= 257.873
KPa
CRUSHING STRENGTH= 773.619
KPa

VELOCITY= 1.0288 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-911,580	-5,947	-270,823	-183,772

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-158,058	-120,455	-99,389	-79,083

****

6) ICE THICKNESS= 1.395984
meters
ELASTIC MODULUS= 1547.238
MPa
FLEXURAL STRENGTH= 257.873
KPa
CRUSHING STRENGTH= 773.619
KPa

VELOCITY= 1.13168 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-942,969	-7,133	-270,823	-185,184

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-170,317	-138,173	-99,389	-79,083

****

7) ICE THICKNESS= 1.423416
meters
ELASTIC MODULUS= 1547.238
MPa
FLEXURAL STRENGTH= 257.873
KPa
CRUSHING STRENGTH= 773.619
KPa

VELOCITY= .72016 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-855,138	-3,013	-291,502	-183,592

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-125,331	-72,291	-101,837	-80,506

TABLE E.2 (con't.)

8) ICE THICKNESS= 1.4478
meters
ELASTIC MODULUS= 1547.238
MPa
FLEXURAL STRENGTH= 257.873
KPa
CRUSHING STRENGTH= 773.619
KPa

VELOCITY= 1.69752 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,198,025	-15,486	-297,036	-224,696

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-251,711	-238.641	-104,024	-91,917

9) ICE THICKNESS= 1.548384
meters
ELASTIC MODULUS= 1547.238
MPa
FLEXURAL STRENGTH= 257.873
KPa
CRUSHING STRENGTH= 773.619
KPa

VELOCITY= 2.52056 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,597,756	-33,031	-322,041	-251,265

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-411,719	-411,594	-113,532	-87,606

10) ICE THICKNESS= 1.624584
meters
ELASTIC MODULUS= 1547.238
MPa
FLEXURAL STRENGTH= 257.873
KPa
CRUSHING STRENGTH= 773.619
KPa

VELOCITY= 3.03496 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,931,157	-47,177	-376,789	-299,782

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-528,733	-513,074	-120,885	-91,894

TABLE E.2 (con't.)

11) ICE THICKNESS= 1.472184 meters
ELASTIC MODULUS= 1861.65 MPa
FLEXURAL STRENGTH= 310.275 KPa
CRUSHING STRENGTH= 930.825 KPa

VELOCITY= .7716 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,022,664	-3,436	-367,750	-235,884
TURNING RESIST.	**TURNING FRICTION**	**SLIDING RESIST.**	**SLIDING FRICTION**
142,119	-85,295	-108,[illegible]	-[illegible]

12) ICE THICKNESS= 1.[illegible]2816 meters
ELASTIC MODULUS= 1861.65 MPa
FLEXURAL STRENGTH= 310.275 KPa
CRUSHING STRENGTH= 930.825 KPa

VELOCITY= 1.5432 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,506,025	-12,904	-457,555	-351,167
TURNING RESIST.	**TURNING FRICTION**	**SLIDING RESIST.**	**SLIDING FRICTION**
265,661	-212,[illegible]30	125.[illegible]65	[illegible].247

13) ICE THICKNESS= 1.575816 meters
ELASTIC MODULUS= 1861.65 MPa
FLEXURAL STRENGTH= 310.275 KPa
CRUSHING STRENGTH= 930.825 KPa

VELOCITY= 1.64608 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,446,967	-14,600	-418,946	-311,908
TURNING RESIST.	**TURNING FRICTION**	**SLIDING RESIST.**	**SLIDING FRICTION**
-271,009	-237,693	-118,328	-89,084

TABLE E.2 (con't.)

14) ICE THICKNESS= 1.740408 meters
ELASTIC MODULUS= 1861.65 MPa
FLEXURAL STRENGTH= 310.275 KPa
CRUSHING STRENGTH= 930.825 KPa

VELOCITY= 1.90328 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,706,129	-19,278	-470,066	-369,904

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-344,363	-289,725	-134,104	-97,968

15) ICE THICKNESS= 1.804416 meters
ELASTIC MODULUS= 1861.65 MPa
FLEXURAL STRENGTH= 310.275 KPa
CRUSHING STRENGTH= 930.825 KPa

VELOCITY= 2.93208 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-2,278,496	-44,154	-511,934	-430,289

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-577,258	-517,569	-140,138	-101,308

16) ICE THICKNESS= 1.347216 meters
ELASTIC MODULUS= 1861.65 MPa
FLEXURAL STRENGTH= 310.275 KPa
CRUSHING STRENGTH= 930.825 KPa

VELOCITY= 4.21808 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-2,203,095	-88,818	-311,838	-246,757

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-751,299	-720,488	-96,546	-76,255

TABLE E.2 (con't.)

17) ICE THICKNESS= 1.499616
meters
ELASTIC MODULUS= 1861.65
MPa
FLEXURAL STRENGTH= 310.275
KPa
CRUSHING STRENGTH= 930.825
KPa

VELOCITY= 1.44032 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,302,714	-11,309	-393,545	-291,123

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-228,235	-194,000	-110,970	-84,841

18) ICE THICKNESS= 1.395984
meters
ELASTIC MODULUS= 1861.65
MPa
FLEXURAL STRENGTH= 310.275
KPa
CRUSHING STRENGTH= 930.825
KPa

VELOCITY= 2.3148 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,468,274	-28,053	-325,141	-253,578

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-353,092	-356,497	-101,011	-78 955

19) ICE THICKNESS= 1.271016
meters
ELASTIC MODULUS= 1861.65
MPa
FLEXURAL STRENGTH= 310.275
KPa
CRUSHING STRENGTH= 930.825
KPa

VELOCITY= 4.73248 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-2,320,511	-110,830	-276,441	-216,033

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-858,653	-807,543	-89,771	-72,069

TABLE E.2 (con't.)

20) ICE THICKNESS= .938784 meters
ELASTIC MODULUS= 1861.65 MPa
FLEXURAL STRENGTH= 310.275 KPa
CRUSHING STRENGTH= 930.825 KPa

VELOCITY= 5.60696 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,732,599	-153,622	-163,034	-122,402
TURNING RESIST.	**TURNING FRICTION**	**SLIDING RESIST.**	**SLIDING FRICTION**
-807,989	-523,504	-62,341	-53,329

21) ICE THICKNESS= 1.014984 meters
ELASTIC MODULUS= 1861.65 MPa
FLEXURAL STRENGTH= 310.275 KPa
CRUSHING STRENGTH= 930.825 KPa

VELOCITY= 5.76128 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-2,327,645	-161,871	-177,147	-134,175
TURNING RESIST.	**TURNING FRICTION**	**SLIDING RESIST.**	**SLIDING FRICTION**
-1,031,509	-858,901	-68,223	-57,690

22) ICE THICKNESS= 1.6764 meters
ELASTIC MODULUS= 1861.65 MPa
FLEXURAL STRENGTH= 310.275 KPa
CRUSHING STRENGTH= 930.825 KPa

VELOCITY= .5144 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,238,046	-1,589	-457,409	-318,329
TURNING RESIST.	**TURNING FRICTION**	**SLIDING RESIST.**	**SLIDING FRICTION**
-135,039	-104,705	-128,003	-94,562

TABLE E.2 (con't.)

23) ICE THICKNESS= 1.472184
meters
ELASTIC MODULUS= 1861.65
MPa
FLEXURAL STRENGTH= 310.275
KPa
CRUSHING STRENGTH= 930.825
KPa

VELOCITY= .61728 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-995,879	-2,247	-367,750	-233,391

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-125,732	-77,388	-108,323	-83,295

24) ICE THICKNESS= 1.575816
meters
ELASTIC MODULUS= 1861.65
MPa
FLEXURAL STRENGTH= 310.275
KPa
CRUSHING STRENGTH= 930.825
KPa

VELOCITY= 2.8292 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,930,221	-41,228	-418,946	-332,428

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-490,508	-480,929	-118,328	-89,084

25) ICE THICKNESS= 1.3716
meters
ELASTIC MODULUS= 1861.65
MPa
FLEXURAL STRENGTH= 310.275
KPa
CRUSHING STRENGTH= 930.825
KPa

VELOCITY= .56584 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-875,661	-1,905	-318,409	-203,165

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-109,432	-68,334	-98,738	-77,584

TABLE E.2 (con't.)

26) ICE THICKNESS= 1.499616
meters
ELASTIC MODULUS= 1861.65
MPa
FLEXURAL STRENGTH= 310.275
KPa
CRUSHING STRENGTH= 930.825
KPa

VELOCITY= .92592 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,113,689	-4,864	-393,545	-258,670

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-161,309	-104,355	-110,970	-84,841

27) ICE THICKNESS= 1.347216
meters
ELASTIC MODULUS= 1861.65
MPa
FLEXURAL STRENGTH= 310.275
KPa
CRUSHING STRENGTH= 930.825
KPa

VELOCITY= 1.33744 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,077,836	-9,815	-311,838	-227,045

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-194,303	-171,850	-96.546	-76.255

28) ICE THICKNESS= 1.167384
meters
ELASTIC MODULUS= 1861.65
MPa
FLEXURAL STRENGTH= 310.275
KPa
CRUSHING STRENGTH= 930.825
KPa

VELOCITY= 3.6008 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,691,824	-65,519	-238,010	-182,416

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-999,102	-569,215	-00,777	-66,305

TABLE E.2 (con't.)

29) ICE THICKNESS= 1.194816
meters
ELASTIC MODULUS= 1861.65
MPa
FLEXURAL STRENGTH= 310.275
KPa
CRUSHING STRENGTH= 930.825
KPa

VELOCITY= 1.69752 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-1,056,735	-15,486	-258,924	-194,232

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-222,894	-229,717	-83,130	-67,838

30) ICE THICKNESS= .938784
meters
ELASTIC MODULUS= 1861.65
MPa
FLEXURAL STRENGTH= 310.275
KPa
CRUSHING STRENGTH= 930.825
KPa

VELOCITY= 3.0864 meters/sec.

RESISTANCE VALUES IN Newtons

TOTAL RESIST.	WATER RESIST.	BREAKING RESIS"	BREAKING FRICTION
-977,947	-48,724	-163,034	-121,821

TURNING RESIST.	TURNING FRICTION	SLIDING RESIST.	SLIDING FRICTION
-329,922	-247.500	-62,041	-53,329

APPENDIX F

UPDATE SEMI-EMPIRICAL ICE RESISTANCE PREDICTION EQUATIONS (SPLICE MODEL)

NOTE: This work represents continuation and improvement of the SPLICE Model which was begun in 1982.

Introduction

During 1982, a major effort was expended to develop a semi-empirical level ice resistance predictor model based on the best available full scale data for icebreaking escorts. The end result of this effort was the creation of the Ship Prediction in Level Ice (SPLICE) Model evolving from the doctoral work of CDR John Naegle. This model was correlated against a database which included full scale results for four ships: the KATMAI BAY, the MACKINAW, the RADISSON, and the STATEN ISLAND. It had been intended to also employ the ice resistance data from the 1982 POLAR Class tests, but these trials were conducted in ice less than two feet thick, and as such, represented a rather marginal database for a ship the size and power of the POLAR SEA.

With the completion of the 1984 Antarctic deployment, a suitable database for the POLAR Class exists with which to test the SPLICE Model. During the Antarctic trials, POLAR SEA transited ice in a "steady state" mode approaching its design limit--six feet thick. A wide range of velocities was also achieved, spanning from near-bollard conditions to over eleven knots. With the further consideration of remarkably uniform ice, the Antarctic trials have unquestionably provided some of the finest full scale data ever assembled for an icebreaker.

Procedure

The methodology followed was identical to that employed in the previous work on the model. First, data was prepared for the model based on the interpretations of the Antarctic study team. In general, this initial step was straightforward because the various parameters of interest had already been quantified. One exception to this rule related to choosing a friction factor for the hull of the ship. Tests conducted several years earlier indicated that the Inerta coating was very slippery, yielding friction factors ranging from .04 to .10, as a function of the applied pressure. However, from observations of the ship in drydock, it was known that the coating wears off. On such occasions for the KATMAI Class, it has been reported that the stripped sections exhibit friction factors approaching .30--20% greater than that for bare steel. Consequently, we chose an intermediate value of .20 for an overall friction factor. It should be noted that the original model tests of the POLAR Class were conducted at this level and the results correspond well with the observed performance.

Next, the model was exercised and individual components of the ice resistance were compared to our intuitive understanding of the icebreaking process. These runs highlighted one discrepancy with the model. Based on hull characteristics of the POLAR Class and thick ice conditions tested in Antarctica, the program predicted that less than 10% of the underwater hull was covered with ice. In turn, this low percentage meant that very little frictional resistance was seen by the ship during the submergence/sliding process. Such a low extent is not realistic.

Predictions of underwater coverage are made by projecting dimensions of the first and penultimate cusps onto the bottom of the ship based on side flare angles at the waterline. For large side flare angles or ice conditions and ship speeds which produce large cusp dimensions, this rationale will predict a very low coverage. However, such low percentages are not real. In actual field trials when a large cusp is broken, it will typically fail into smaller wedges as it is forced down. These smaller pieces will more readily coat the hull than would be the case if the huge cusps stayed intact. However, this phenomenon is beyond the scope of the model; therefore, a simpler routine is required to predict more realistic coverages.

In examining past runs of the model for ships other than the POLAR Class, typical coverages ranged in the 40% to 60% bracket. These values are much higher because other vessels have less side flare and operate in considerably lighter ice conditions than the POLAR SEA. These values also seem more reasonable in light of ice piece dynamics observed in model tests. Consequently, a new routine was added which imposed a limit for ice coverage corresponding to 50% of projected waterplane area. On runs in which the calculated area is less than this limit, the limit will apply; otherwise, at greater than 50% the calculated area will be used. This change would have little effect on previous runs. Based on a sampling of data, we estimate that this modification would have less than a 10% increase on total resistance. However, for the POLAR SEA, results will be more dynamic and also more meaningful.

The final step was to conduct an optimization process for the POLAR SEA alone. Four coefficients were considered as with earlier optimization runs. The "snow multiplier" effect on friction components was neglected; there was much too little data to support this parameter. Results of optimization focused on a single coefficient--that associated with the cusp depth predictor equation. From the original optimization work, cusp depth was linked to hull form by a coefficient given as:

$$k = 1.412\ n_3 \qquad \text{(F-1)}$$

where n_3 represents the average directional cosine in the bow region. Using the POLAR SEA data indicated that the prediction given by the above equation was too low by 20%. Inasmuch as the hull form of the POLAR Class is beyond all other icebreakers we have tested, it is not surprising that this effect is present. In theory, as side flare angle approaches 90 degrees, cusp depth must approach infinity. Thus, a parabolicly shaped curve would not be unreasonable for this parameter. For future runs, the following equation is suggested for predicting the cusp depth coefficient for directional cosines greater than .649:

$$k = 50.656\ n_3^2 - 64.339\ n_3 + 21.336 \qquad \text{(F-2)}$$

At values less than .649, the linear equation described above (Equation F-1) should still be used. This division of the equation permits the earlier optimization runs to hold while still reconciling our changes due to POLAR SEA data. Figure F-1 illustrates the effect of this hybrid equation on the coefficient.

Results

Input data for the runs is shown in Tables F.1 and F.2. Table F.1 presents ship characteristics in a similar format to the companion Transport Canada study which provided data for earlier work. Table F.2 presents ice conditions data, except for flexural strength, which was uniformly set at 44 psi for Antarctic runs and 50 psi for Bering Sea data.

Predictions of the SPLICE Model updates, as noted above, are listed in the last column of Table F.2 and presented graphically in Figure F.2 (measured data are shown in Figure F.3). Overall, the model predicted 31.3% of the events within 10% of the measured values and 70.3% of the events within 25% of that observed. A scatter diagram of the accuracy versus ice thickness and ship velocity is shown in Figure F.4. In general, this diagram indicates random scatter except for high speed/thin ice combinations. In this latter regime, the model underpredicts resistance by about 30%. This effect may be due to an artificially large length of thin pieces. This distortion would effect all resistance processes in rather complex ways, though overall it is likely to lower predicted resistance. A simplification was made to limit the number of cusp rows created and thereby enhance run time. It was assumed at that time that this regime was of marginal importance to the user.

Recommendations to Users of SPLICE

The following recommendations are made to future users of the SPLICE Model:

- Use care when defining friction factor for the hull. This term significantly impacts model results. In full scale field trials, this factor is likely to vary over time for ships with degradable coatings such as Inerta. In the case of the POLAR Class, a representative value of .20 has been shown effective.

- Override projected area calculations (made for sliding friction resistance) if the calculated area falls below 50% of the projected waterplane area. Heavy ice conditions, high speeds, or high side flare are all likely to invalidate assumptions on which this equation is based.

- Adopt a parabolic equation of the form:

$$k = 50.656\ n_3^2 - 64.339\ n_3 + 21.336$$

  for the cusp depth equation for all ships with a mean directional cosine of .649 or greater. This new equation is based on optimizing the model on the POLAR Class which has an "n_3" of .712, which is significantly larger than that tallied for any ship previously used.

TABLE F.1 SHIP DATA SHEET

1. SHIP'S NAME - POLAR STAR, POLAR SEA

2. TYPE OF TESTS CONDUCTED

	TEST TYPE	DATE	PLACE	ESTABLISHMENT	DATA POINTS
Full Scale	Ice Trials	Apr/82	N. Bering Sea	ARCTEC, Inc.	34
	Ice Trials	Jan/84	Antarctic	ARCTEC, Inc.	30

3. MAIN SHIP CHARACTERISTICS

	Δ (LT)	L_{oa} (ft)	B (ft)	T (ft)	Power (shp)	No.of Props	Diam. (ft)	Pitch Diam.	CP FP
Full Scale	13,190	399	83.5	31.8	18,000 D-E 60,000 G-T	3	16.0	*	CP

* Variable Pitch Propeller

4. BOW ANGLES AND DWL OFFSETS

- Stem Angle $\gamma_0 = 15.5°$, - Flare Angle $\beta_5 = 60.0°$

Station	10	9	8	7	6	5	4	3	2	1	0
α (°)	0.00°	0.00°	0.00°	3.00°	7.00°	11.00°	16.00°	19.00°	24.00°	26.50°	28.00°
β (°)	12.00°	12.00°	12.00°	12.00°	17.00°	23.00°	35.50°	42.00°	48.00°	55.50°	59.00°
OFFSETS (ft)	38.45	38.72	39.00	38.47	37.25	34.73	30.80	25.35	18.25	9.67	0.00
STATION	20	19	18	17	16	15	14	13	12	11	10
OFFSETS (ft)	0.00	9.67	17.61	24.18	28.78	31.45	34.36	35.59	36.87	37.65	38.45

TABLE F.2 TEST DATA AND SPLICE MODEL RESULTS

ICE THICKNESS (ft)	AVERAGE SPEED (kts)	MEASURED RESISTANCE (lbs)	PREDICTED RESISTANCE (lbs)
ARCTIC DATA			
.60	3.8	25,753	33,749
1.60	.8	97,413	73,716
1.60	1.0	96,129	78,921
1.60	1.4	78,530	80,754
1.60	5.4	170,519	135,512
1.60	10.0	304,398	155,321
1.60	8.3	314,647	156,820
1.60	.6	97,981	70,087
1.60	1.7	85,409	88,879
1.60	1.4	94,205	80,754
1.60	4.5	164,530	123,684
1.60	3.7	200,062	120,262
1.60	4.2	207,658	121,624
1.60	10.3	218,664	158,616
1.60	12.6	179,910	194,827
1.50	.7	54,698	62,492
1.50	4.0	94,522	108,733
1.50	7.3	109,111	146,612
1.50	7.5	182,259	145,394
1.50	8.6	203,946	142,703
1.56	10.9	299,266	163,894
1.60	6.1	280,663	159,522
1.60	4.6	169,257	128,855
1.60	14.3	274,855	208,561
1.30	1.6	64,461	66,115
1.30	4.8	103,442	106,084
1.30	8.7	110,008	113,987
1.30	3.2	102,360	83,505
1.30	6.6	155,238	116,018
1.00	1.4	32,782	44,565
1.00	12.5	171,557	110,141
1.00	8.5	104,074	82,939
1.00	9.6	143,482	82,943
1.00	6.7	124,413	88,184

TABLE F.2 TEST DATA AND SPLICE MODEL RESULTS (Continued)

ICE THICKNESS (ft)	AVERAGE SPEED (kts)	MEASURED RESISTANCE (lbs)	PREDICTED RESISTANCE (lbs)
ANTARCTIC DATA			
4.00	1.1	350,620	231,083
4.00	3.5	446,112	355,911
4.25	.9	231,846	241,109
4.25	1.3	321,865	276,500
4.58	2.0	396,692	371,225
4.58	2.2	398,611	386,441
4.67	1.4	363,319	320,343
4.75	3.3	435,360	469,580
5.08	4.9	590,943	627,021
5.33	5.9	747,206	731,225
4.83	1.5	373,889	344,671
5.42	3.0	476,723	571,045
5.17	3.2	531,968	546,392
5.71	3.7	605,490	680,088
5.92	5.7	825,289	870,248
4.42	8.2	659,230	703,313
4.92	2,8	514,655	477,127
4.58	4.5	503,711	488,822
4.17	9.2	591,073	607,173
3.08	10.9	476,022	374,798
3.33	11.2	489,067	420,972
5.50	1.0	613,790	355,107
4.83	1.2	263,832	320,274
5.17	5.5	574,006	669,065
4.50	1.1	442,581	278,853
4.92	1.8	560,017	380,221
4.42	2.6	331,640	370,651
3.83	7.0	499,645	578,896
3.92	3.3	382,414	338,297
3.08	6.0	375,989	349,968

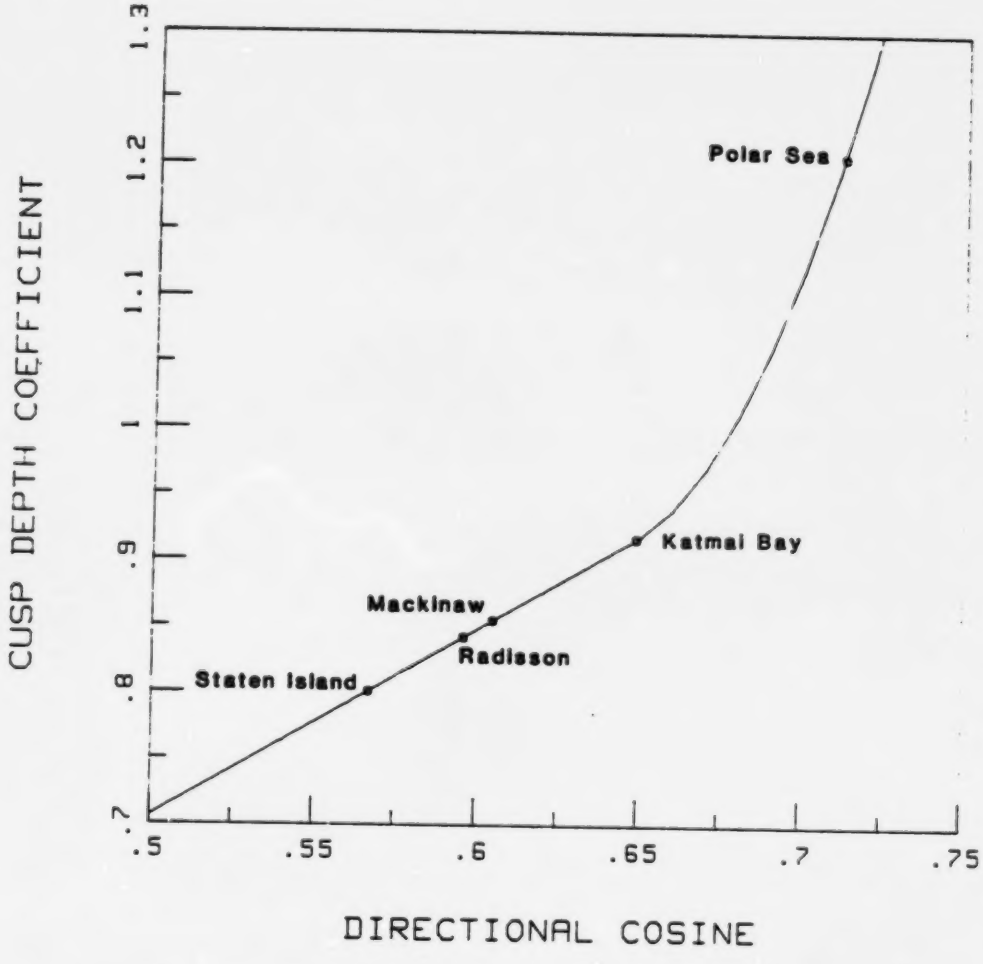


Figure F-1 **Hull Geometry Effects on Cusp Depth**

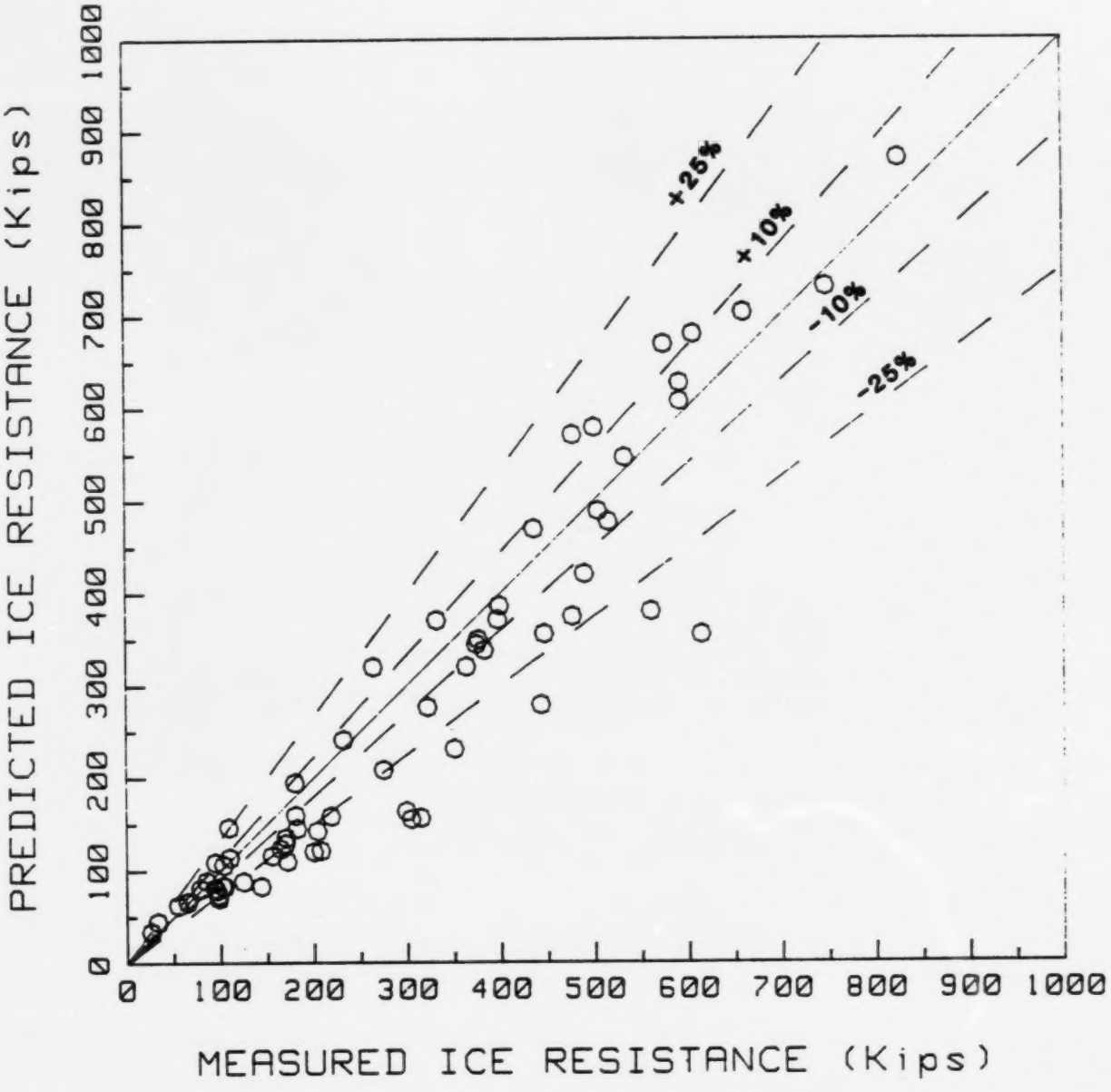


Figure F-2 POLAR CLASS

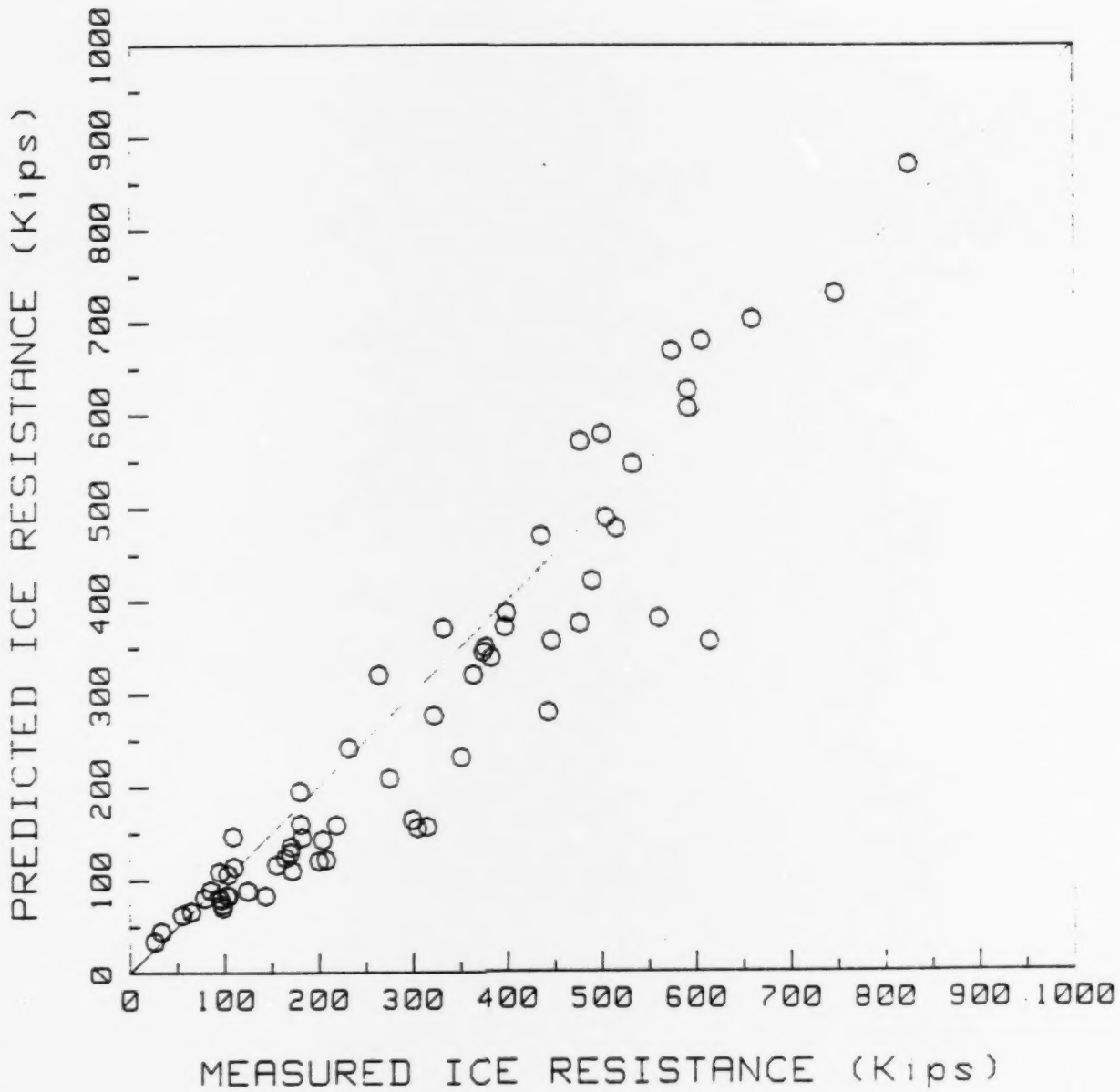

PREDICTED ICE RESISTANCE (Kips)
0
100
200
300
400
500
600
700
800
900
1000
MEASURED ICE RESISTANCE (Kips)

Figure F-3

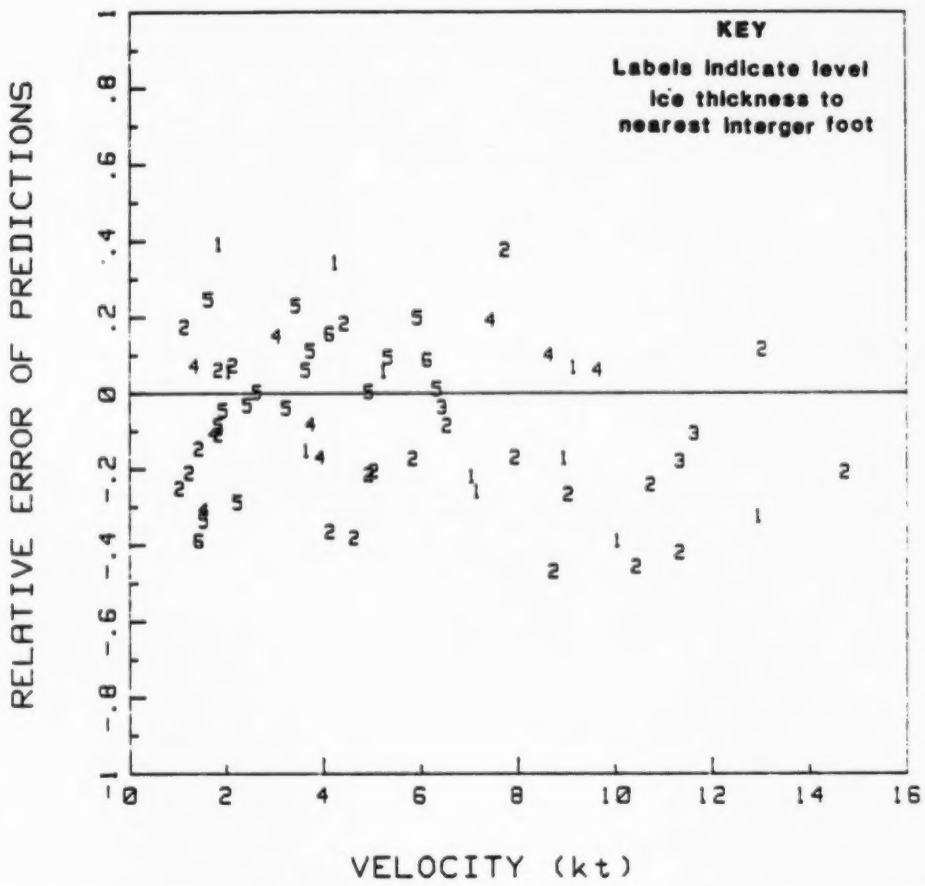


FIGURE F-4 Error Analysis of SPLICE Results for the POLAR CLASS